Experimental and Numerical Analysis with MSC Marc Software for the Characterization of Two-component Moulded Parts

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The study investigates the effect of several injection moulding parameters, such as the melt and mould temperature, on the adhesion obtained at the moulding of bi-component tensile test specimens. Mono- and bi-component specimens were subject to uniaxial tensile tests. The aim is to obtain a model analysis for the study of the mechanical behaviour of bi-component parts submitted to uniaxial tensile tests. The localised information on the state of stresses and strains at the interface between the two polymeric components is obtained through this analysis.The use of the G'Sell-Jonas model offers a good prediction regarding the mechanical behaviour of the two component tensile test specimens on both the elastic and the plastic regions. The simulation of the mono-component tensile test showed a good agreement between the experimental and the predicted results, with a correlation coefficient ranging between 0.9973 and 0.9998. High levels of confidence were obtained for the mono-component tensile test specimen results, further applied for FEA analysis of the two-component specimen (HDPE/LDPE). The necking effect observed in the experiments, at a 255°C melt temperature for the LDPE, was similar to the one revealed by the finite element analysis.

Keywords: polymers, adhesion, tensile test, FEA

The bi-material moulding technologies are effective process methods to produce polymer products with customised visual, touching, or performance qualities like mechanical strength, improved elasticity.

These moulding processes have been explored in recent years to produce functional and integrated products that have special surface functions such as conductive layer (the use of CNT reinforced polymeric materials) or integrated features that can reduce downstream assembly processes to reduce products cost [1-5].

Multi-material moulding is the injection moulding process where one material is moulded onto a second material to form hybrid structure components. Each material can be used at the optimal level to provide mechanical strength or/and soft touch enhancements. More over, the adhesion obtained through this particular injection moulding process can exhibit a better mechanical behaviour in time compared with the case where adhesives are used. The obtained joint is not susceptible to ageing or other defects that may occur when adhesives are used. This is particularly important where manufacturers are looking to gain technological advantages over rivals by adding value to products from both structural and aesthetics point of view. While tooling costs can be high, by eliminating assembly steps cost savings can be made. Assembly costs may be reduced by up to 20% while total manufacturing cycle time may be trimmed by 20% due to less handling of the part [6].

The advantages of both conventional injection moulding and multi material injection moulded parts regard a high degree of manufacturability, reduced manufacturing time cycle, safety, ergonomics and product functionality aspects.

The introduction of finite element software has made a significant impact in industry. Its use in the design phase of new industrial products has resulted in cost reduction relative to the manufacture of physical prototypes and "trial and error" tests.

The most challenging operation when modelling thermoplastic materials is setting the input data into the finite element software with the appropriate experimental results, in order to represent the materials' mechanical behaviour and determine suitable material models for plastic components [7-11]. Usually, the material models are obtained using data from the traditional uniaxial tensile test.

MSC Marc Mentat is one of many available softwares on the market, that helps to simulate the nonlinear stress analysis in the static and dynamic regimes. The analysis of the two-component parts using the finite element software can reduce the costs when designing new parts. Mechanical behaviour of finished part can be predicted offering the possibility of improving the design on structural behaviour of the part from the designing stage of the part.

Since our study is focused on the tensile behaviour of the two-component specimens, the G'Sell model was fitted with experimental results from the tensile tests.

Experimental part

Materials and methods

For this study two polymeric materials were selected. A low density polyethylene (LDPE) Ropoten FV 20-205-3 from Lukoil (Bulgaria), and high density polyethylene (HDPE) 277-73 from JSC Kazanorgsintez (Russia) were used to mould both monocomponent and two-component specimen. The density and melt flow rate for LDPE and HDPE was 919 and 962kg/m^3 and the melt flow rate was 1.8g/10min and 2.5g/10min, respectively. For two-component moulding HDPE was used as substrate and LDPE as overmould.

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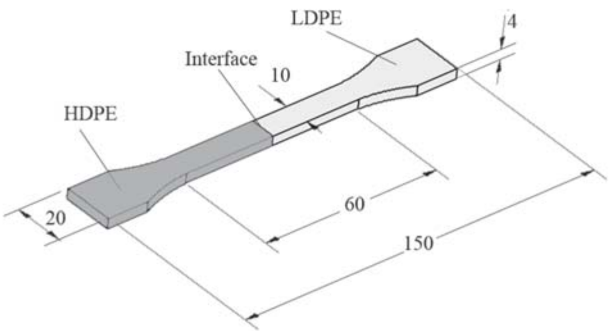

Fig. 1. Tensile test specimen dimension and configuration according to SR EN ISO 527-2

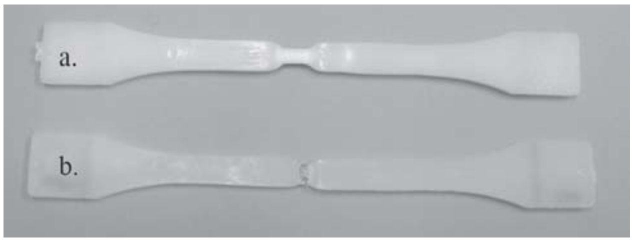

Fig. 2. Tested mono-component specimens: (a) HDPE (T_{melt} 255°C, T_{mold} 50°C), (b) LDPE (T_{melt} 255°C, T_{mold} 50°C)

Table 1
INJECTION MOLDING PARAMETERS FOR BOTH MONO AND TWO-COMPONENT TENSILE TEST SPECIMEN MOLDING

Process paratemer	HDPE	LDPE
Melt temperature [°C]	255	215, 255
Mold temperature [°C]	50	30, 50
Injection pressure [MPa]	100	100
Injection time [s]	1	1
Holding pressure [MPa]	70	85
Holding time [s]	10	7
Cooling time [s]	35	35

Table 2
FORCE AND ELONGATION AT BREAK FOR LDPE MONOCOMPONENT SPECIMENS

Material	Moulding conditions		Elongation at break [mm]		Force at break [N]	
	T_{melt} [°C]	T_{mold} [°C]	Mean	Std. Dev.	Mean	Std. Dev.
LDPE	215	30	94.709	5.812	365.754	8.687
	215	50	93.549	5.604	380.850	11.369
	255	30	93.087	3.069	345.438	9.187
	255	50	96.312	1.835	322.394	7.884
HDPE	255	50	70.406	19.586	469.264	11.377

Injection moulding experiments

The part subject to this study is a tensile test specimen according to SR EN ISO 527-2 standard and figure 1 illustrates the geometry of the specimen. The specimen dimensions are in mm.

The monocomponent tensile test specimens were moulded using a conventional injection moulding machine, Arburg Allrounder 320C Golden Edition. The machine has a clamping force of 500kN and is equipped with a hydraulic heating system for the mould temperature control. The injection moulding parameters used for both polymers are presented in table 1.

Two-component tensile test specimens are obtained through the injection moulding process. Figure 1 illustrates the geometry of the specimen and the particular geometry of the two materials interface. The two-component tensile test specimens were moulded in a two stage injection moulding process using an Arburg Allrounder 320C Golden Edition injection moulding machine. First, the HDPE was injected to obtain the substrate for the tensile test specimen, using a metallic insert. The substrate was ejected from the mould cavity, cooled and used in the second stage as an insert when overmoulding the LDPE onto the moulded HDPE substrate part. The injection moulding parameters for both substrate and overmould are presented in table 1. Due to the fact that the substrate moulding conditions do not influence the adhesion between the two polymeric materials, they were kept constant.

The tensile test of specimens

After tensile test specimen moulding, the uniaxial tensile tests have been carried out on a universal testing machine (Testometric M350-5AT) with a cross speed of 5mm/min at room temperature (25°C). A number of eight specimens were tested for each injection moulding conditions (table 1). Figure 2 presents the fractured mono-component specimens. In the case of HDPE, the mechanical behaviour shows high strains values at tensile tests made with a cross speed of 5mm/min. Due to the limitations of the crosshead displacement of the testing machine to 1000mm and to the mechanical behaviour of HDPE, the tensile tests on HDPE were stopped after the initiation of the necking phenomenon (fig. 2).

Table 2 presents the mean values and standard deviation of force and elongation at break for mono-component specimens at different moulding conditions. The results at break for HDPE, presented in table 2, are not representative due to the fact that the tests were stopped after the necking initiation (fig. 3).

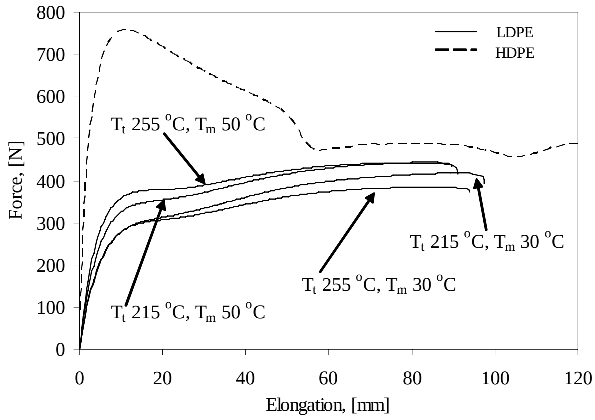

Fig. 3. Force-displacement experimental curves for LDPE at T_{melt} 215°C; T_{mold} 30°C, 50°C and T_{melt} 255°C; T_{mold} 30°C, 50°C and HDPE at T_{melt} 255°C; T_{mold} 50°C

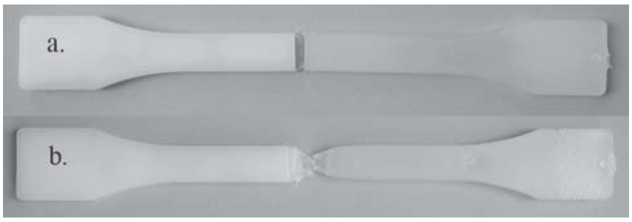

Fig. 4. Two-component specimens after rupture: (a) HDPE/LDPE (T_{melt} 215°C, T_{mold} 50°C), (b) HDPE/ LDPE (T_{melt} 255°C, T_{mold} 50°C).

Table 3
FORCE AND ELONGATION AT BREAK FOR TWO-COMPONENT SPECIMENS

Nr. Crt.	T_{melt} [°C] HDPE	T_{melt} [°C] LDPE	T_{mold} [°C]	Elongation at break [mm] Mean	Elongation at break [mm] Std. Dev.	Force at break [N] Mean	Force at break [N] Std. Dev.
1	255	215	30	3.422	0.276	225.688	8.325
2		215	50	7.938	0.742	293.54	11.131
3		255	30	31.545	8.757	328.834	29.115
4		255	50	29.905	6.770	337.482	22.546

Figure 2 presents the force-elongation curves for LDPE mono-component specimens. The increasing of the mould temperature also increases the force measured during the plastic region of deformations, with small differences in value at break.

Figure 4 presents the failure mode of the bi-component specimens at a different melt temperature and a constant mould temperature. For T_{melt} 215°C and T_{mold} 50°C, failure occurs at the bi-component interface, while for T_{melt} 255°C and T_{mold} 50 °C, the failure occurs inside LDPE. This means that the adhesive bond obtained when moulding LDPE at T_{melt} 255°C temperature is good. The mean values and standard deviation of the breaking force and elongation for all the moulding conditions are presented in table 3.

Figure 5 shows that, for a melting temperature of 215°C, the breaking strength values between both polymers are around (150÷240)N, in which cases the fracture occurs at the interface between the two polymers. When the specimen LDPE is overmoulded at T_{melt} 255°C, the breaking force values are around 350N and the fracture occurs in the low density polyethylene material.

The force-displacement curves of the experimental data obtained for the HDPE/ LDPE two-component specimens at a constant T_{melt} of 215°C and a variable T_{mold} ranging between 30 and 50°C are presented in figure 5a. Due to the low adhesion values obtained, the failure is brittle like. The increase of the mould temperature also increases the adhesion and that gives the two-component specimen the possibility to deform during tensile tests. In the case of a constant 255°C melt temperature, a higher adhesion is obtained and thus the force-displacement curves presented in figure 5b show a mechanical behaviour close to the LDPE mono-component results; this is due to the deformation of the two-component specimen inside the LDPE part.

Modelling the uniaxial tensile test in marc for mono and two component specimens

Identification of the G'Sell-Jonas model coefficients

Here, we model the behaviour of the two different polymeric materials on the bases of the pioneer work by G'Sell and Jonas [7, 12, 13], and using a multiplicative equation, $\sigma = f(\varepsilon)$. Such a relationship was verified with a number of polymers [14, 15]. In this constitutive relation, the first term is written as

$$f(\varepsilon) = K \cdot Y(\varepsilon) \cdot H(\varepsilon)\,, \qquad (1)$$

where *K* is a scaling factor sometimes referred to as the "consistency factor" [16], $Y(\varepsilon)$ represents the viscoelastic response up to the yield point, and $H(\varepsilon)$ is the strain-hardening function that describes the progressive consolidation induced by plastic deformation. In the case of semicrystalline polymers, a Maxwell-type viscoelastic expression

$$Y(\varepsilon) = [1 - \exp(-w \cdot \varepsilon)], \qquad (2)$$

is used and the strain-hardening is better described by the function

$$H(\varepsilon) = \exp(h \cdot \varepsilon^n). \qquad (3)$$

Introducing the terms $Y(\varepsilon)$ and $H(\varepsilon)$ in the equation 1, the G'Sell-Jonas model was obtained

$$\sigma = K \cdot \left(1 - e^{-w\varepsilon}\right) e^{h\varepsilon^2}, \qquad (4)$$

which made it possible to describe the stress-strain behaviour of viscoelastic materials. The stress is obtained by a function of the strain and hardening of the material after the yield stress, where *K* is the "consistency factor"

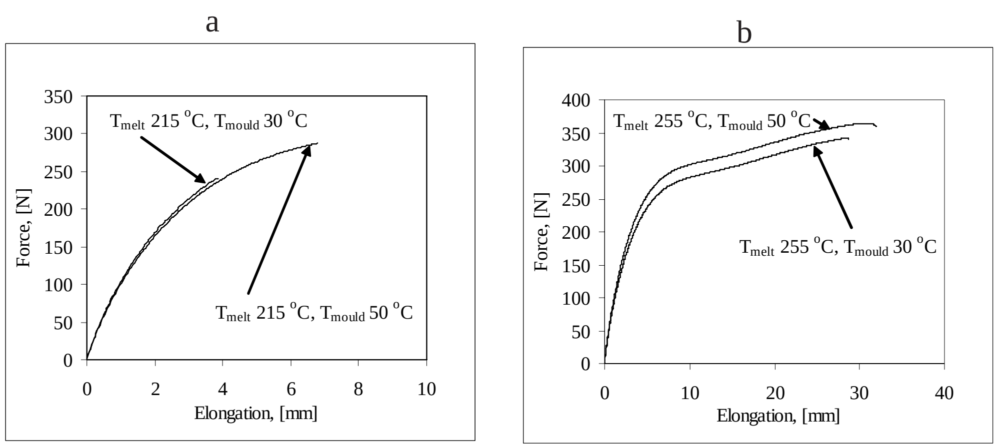

Fig. 5. Force-displacement experimental curves for two-component injection molding experiments LDPE molded at: a. T_{melt} 215°C; T_{mold} 30°C and T_{mold} 50°C; b. T_{melt} 255°C; T_{mold} 30°C and T_{mold} 50°C

Material	Moulding conditions		G'Sell model coefficients			Correlation coefficient
	T_{melt} [°C]	T_{mold} [°C]	K	h	w	R^2
LDPE	215	30	8.358	4.096	23.29	0.9999
	215	50	9.570	3.660	26.24	0.9998
	255	30	8.413	3.576	24.37	0.9999
	255	50	10.410	3.075	28.95	0.9998
HDPE	255	50	20.670	1.793	47.66	0.9973

Table 4
EXPERIMENTAL PARAMETERS OF THE G'SELL MODEL

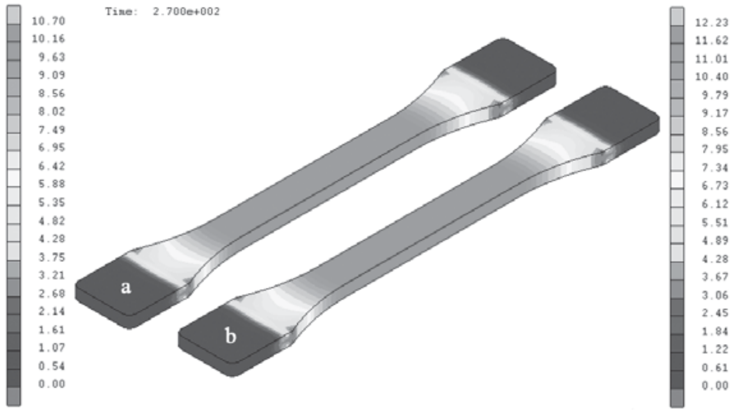

Fig 6. The distribution of σ_{XX} for LDPE at T_{melt} 215°C, (a) T_{mold}30°C and (b) T_{mold} 50°C

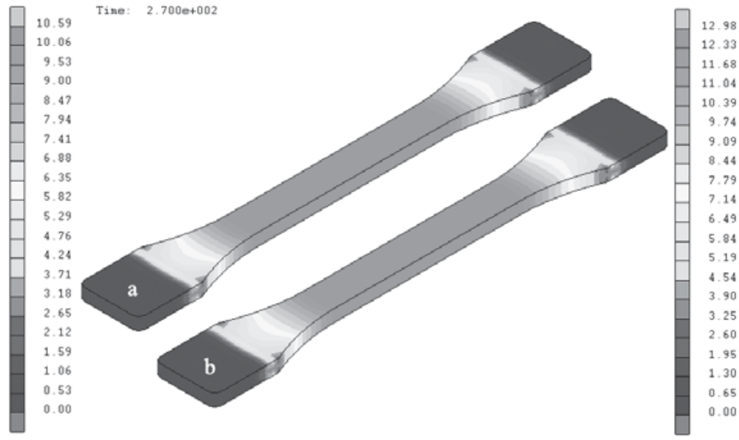

Fig. 7. The distribution of σ_{XX} for LDPE at T_{melt} 255°C, (a) T_{mold}30°C and (b) T_{mold} 50°C

[16], and h and w represent the model coefficients that need to be determined

$$\sigma_1 = K \cdot \left(1 - e^{-w\varepsilon}\right), \quad \sigma_2 = e^{h\varepsilon^2} \tag{5}$$

The G'Sell-Jonas model offers a good result, reproducing the stress-strain behaviour of the material in the whole strain area [12, 13, 15, 17-19].

In what follows, the validity of this law will be checked and the most suitable set of parameters (K, w and h) for the two materials will be determined. The fitting procedure and model coefficients extraction were realised with a custom program written in Matlab. The best constitutive parameters thus obtained (K, w, and h) are presented in table 4.

The fitting models were applied only for a maximum value of 0.25 for the true strain due to lower elongation observed at two-component specimen testing. The fitted curves shows a good correlations between experimental data and G'Sell-Jonas modelling of the data on both the viscoelastic and the plastic zones, with a correlation coefficient (R^2) between 0.9973(HDPE) and 0.9998(LDPE).

Modelling the uniaxial tensile test in Marc software for mono-component specimens

The validation of a material model should be carried out in simple reproducible geometries that require a low computational cost in the FEA software.

The finite element analysis model was used in order to identify and quantify the state of stress and strain at the surface interface between the two moulded polymers only for the results obtained for a melt temperature of 215, 255°C and for a mould temperature of 30 and 50°C.

G'Sell model coefficients (table 4) were determined in respect with the moulding conditions for both materials, and inserted in Marc models for modelling the material behaviour.

Modelling the material behaviour is one of the most important factors since the simulation response will mainly depend on how well the structural behaviour of the material is represented in software.

The calculations performed are quasi-static solutions. The presence of material non-linearities, makes the solution convergence difficult in some cases [20]. Therefore, a selection of a correct number of solution substeps is fundamental for the consecution of the required results.

The mesh was realised with a number of 4448 hexahedral elements.

According to the experiment, the specimen was clamped at the end A, and a displacement was applied at the end B.

The strain and stress distributions at a given moment can be seen in figures 6 and 7 to explain the differences between different moulding conditions. All results of the stress distribution are displayed in MPa.

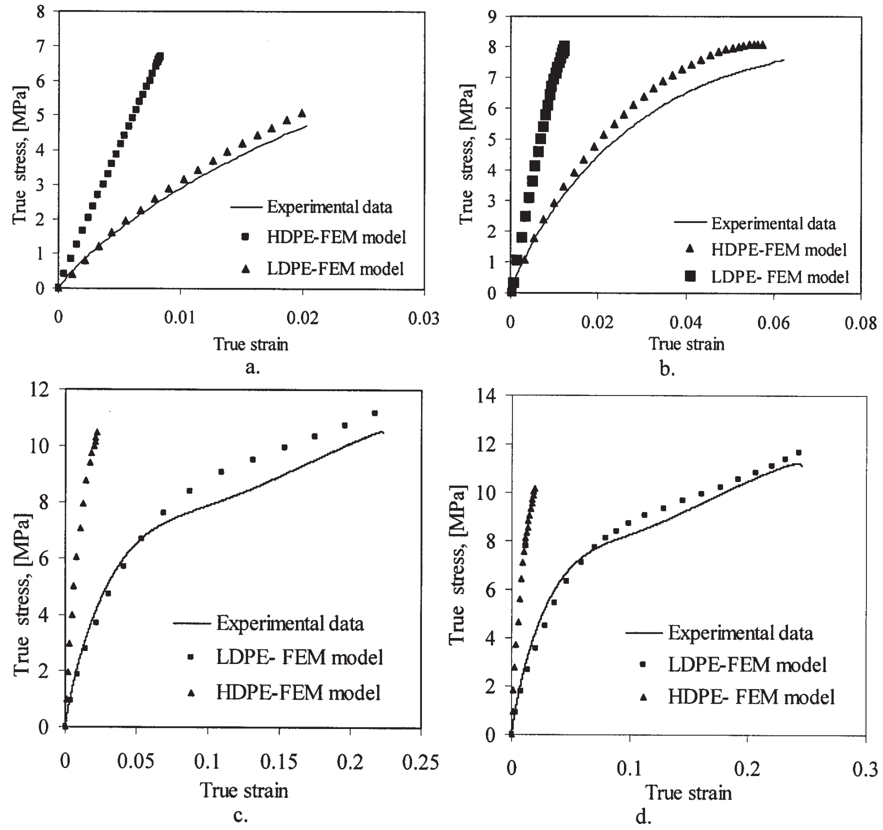

Fig. 8. Comparison of the stress-strain curves: experimental data and FEA data predicted for two-component specimen LDPE overmoulded at (a) T_{melt} 215°C, T_{mold} 30°C; (b) T_{melt} 215°C, T_{mold} 50°C; (c) T_{melt} 255°C, T_{mold} 30°C; (d) T_{melt} 255°C, T_{mold} 50°C.

The G'Sell models were applied only for a maximum value of 0.25 for the true strain. The fitting shows good correlations of the data on both the viscoelastic and the plastic zones, with a correlation coefficient (R^2) between 0.9982(HDPE) and 0.9997(LDPE).

Modelling the uniaxial tensile test in Marc software of bicomponent specimens

The FEM model of the bi-component specimens consists of two bodies bound together, each of which having the characteristics of one of the materials considered. Each body was modelled with a number of 2224 hexahedral elements.

According to the experiment, the specimen was clamped at the HDPE end and a 5 mm/min. displacement was applied at the LDPE end.

The mechanical properties of the materials were determined on the mono-component specimens. The G'Sell model coefficients (table 4) were determined in respect with the moulding conditions for both materials and inserted in the Marc models for modelling the behavior of the materials.

The FEM modelling of the separation of the two bodies was made by introducing a separation criterion involving the introduction of a threshold force at which the separation of the nodes of the two bodies occurs. The value for the separation force was obtained from the experimental tensile tests.

The mechanical behaviour of two-component specimen is closely related to the LDPE's mechanical behaviour, with the observation that, due to specific conditions on the interface between HDPE and LDPE obtained through the injection moulding process, the two-component tensile test specimen reaches the failure at the interface in almost all the studied cases. For a melt temperature of 255°C and a mould temperature of 50°C (as injection moulding conditions), the failure of the two-component specimen occurs in the LDPE material, the obtained bonding between the two polymeric materials being higher than the failure limit of the LDPE.

The FEA simulation regarding the stress-strain evolution on a two-component tensile test specimen presented in figure 8 reveals a slight difference between the experimental and the FEA results, with a correlation coefficient between the experimental data and the LDPE-FEM model ranging between 0.9953 and 0.9994.

In the case of 215°C melt temperature the predicted values at failure are about (1÷5)MPa, the adhesion between the two polymeric materials was poor, whereas, for a melting temperature of 255°C, the predicted values at failure are about (10÷12)MPa, which is the tensile stress at failure of the LDPE. This means that at higher temperature the obtained adhesion can be equal to the strength of LDPE. Remelting phenomenon at the interface is accentuated and the adhesion between the two distinct polymers is higher than the lowest strength of the two polymers.

The curves in figure 8 were drawn at the interest points, at 1 mm of the interface between the two polymers. The location of the interest points can be seen in figure 9. All graphical results of stress distribution are displayed in MPa.

The strain and stress distributions at a given moment can be seen in figure 9.

The necking phenomenon is obtained in the case of the two-component specimen moulded at a 255°C melt temperature and a 50°C mould temperature (fig. 10). In figures 10 and 11, the results shows the stress distribution on the two-component specimen at a close moment

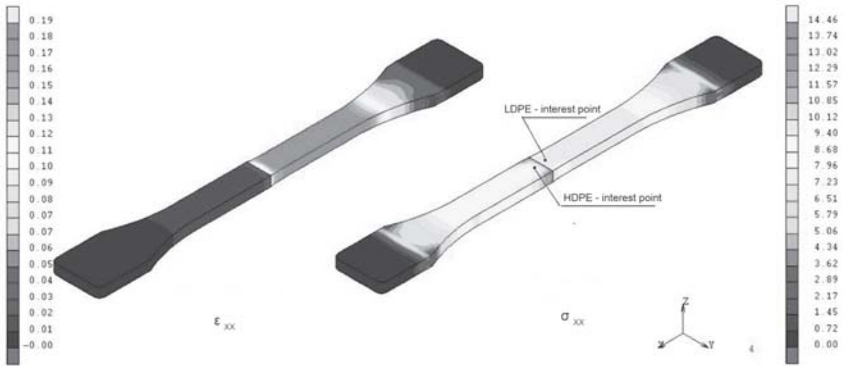

Fig.9. ε_{xx} and σ_{xx} distribution for two-component specimen, LDPE overmolded at T_{melt} 255°C, T_{mold} 30°C

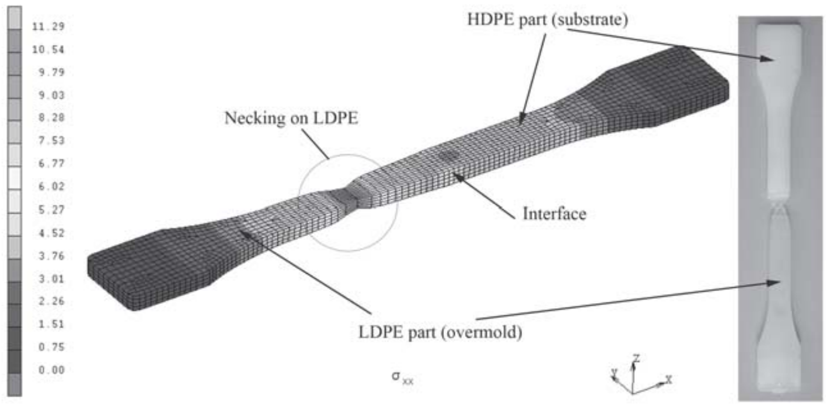

Fig. 10.σ_{xx} on tensile test of two-component specimen moulded at melt temperature of 255°C and mould temperature of 50°C

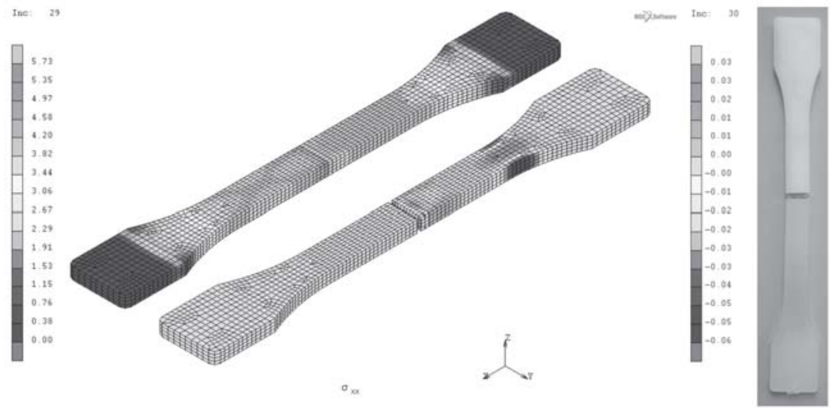

Fig. 11. σ_{xx} component on tensile test of two-component specimen moulded at melt temperature of 215°C and mold temperature of 50°C

before failure. The necking effect that occurred in the experiment at 255°C melt temperature, followed by the failure in the LDPE material, was also obtained in the simulation.

In figure 11, the results are showed at two moments (before and after the break), from the end of the tensile test simulation for the two-component specimen moulded at a 215°C melt temperature and a 50°C mould temperature.

Conclusions

A FEA model is created using Marc Mentat software to simulate the standard ASTM D527 uniaxial tensile test. The G'Sell constitutive model describes the stress-strain constitutive relationship of the polymers under constant loading.

The simulation of the mono-component tensile test showed a good agreement between the experimental and the predicted results, with a correlation coefficient ranging between 0.9973 and 0.9999. High levels of confidence were obtained for mono-component tensile test specimen results, further applied for the FEA of the two-component specimen (HDPE/LDPE). The use of the G'Sell constitutive model offers a good prediction regarding the mechanical behaviour of the two component tensile test specimen on both the elastic and the plastic regions.

Mechanical behaviour of two-component specimens is closely related to the LDPE polymeric material. FEA stress-strain curves revealed some similarities between two-component and LDPE stress-strain curve. The resulting behaviour and failure of the two-component specimen is therefore more related to LDPE component which also has the lower tensile strength between the two polymeric materials.

The necking effect observed in the experiments, at a 255°C melt temperature of the LDPE, was similar to the one revealed by the finite element analysis.

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List of symbols and notations

HDPE - high density polyethylene
LDPE - low density polyethylene
FEA - finite element analysis
FEM - finite element model
T_{melt} - melt temperature
T_{mold} - mold temperature
σ - stress
ε - strain
K - consistency factor

Y(ε) - viscoelastic response up to the yield point
H(ε) - strain-hardening function
h, w - G'Sell constitutive parameters
R^2 - correlation coefficient

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