Materials Today: Proceedings xxx (xxxx) xxx

Contents lists available at ScienceDirect

Materials Today: Proceedings

journal homepage: www.elsevier.com/locate/matpr

Validation method for thickness variation of thermoplastic microcellular foams using punch-tests

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ARTICLE INFO

Article history:
Received 3 December 2019
Received in revised form 12 February 2020
Accepted 29 February 2020
Available online xxxx

Keywords:
Thermoplastics
Viscoelastic-viscoplastic deformation
Thickness variation
Punch-test
Surface detection

ABSTRACT

This paper is concerned with a punch-test based experimental validation method and the investigation of thickness variation in forming process of a thermoplastic material. One of the key factors that characterize the final geometry of thermoformed parts is thickness variation. The material characterization process is usually based on uniaxial measurements performed at different temperature levels being relevant for the thermoforming process. Consequently, the material model can be inaccurate in biaxial stress state, which is dominant in thermoforming process. In this contribution a punch-test based validation method is presented via the case-study of a thermoplastic microcellular polyethylene-terephthalate (MC-PET) foam material. In the proposed method the thickness variation is investigated both experimentally and numerically, by means of laser scanning method and FE simulations. Finally, the utilization of the proposed method as a validation tool for the evaluation of material models that are fitted to uniaxial test data is also demonstrated.

Selection and peer-review under responsibility of the scientific committee of the 36th Danubia Adria Symposium on Advances in Experimental Mechanics.

1. Introduction

Thermoforming is a widely applied industrial process, in which the thermoplastic polymer sheet is heated above its glass transition temperature and gets stretched [1]. Using this process, a great variety of products can be manufactured including parts with extremely thin wall-thickness and very complex geometries. In the industry, there is significant need for the proper characterization of thermoplastic materials for developing accurate finite element (FE) simulations in order to predict and accelerate the whole production process [2]. During the forming procedure the raw thermoplastic material undergoes large stains and nonlinear deformations which show temperature-dependent viscoelastic-viscoplastic properties [1,4]. In the literature, the available constitutive models usually consist of parallel viscoelastic and viscoplastic branches like the two-layer viscoplastic model (TLVP) or the models proposed in the PolyUMod library [3–5].

One of the key factors that characterize the final geometry of the part is thickness variation. In addition, during the forming process the stress state is considered to be rather biaxial than uniaxial. However, the material characterization process is usually based on uniaxial measurements including creep, relaxation and cyclic tests performed at several temperatures [5]. For such nonlinear constitutive models, a perfectly fitted model to uniaxial tests may lead to extreme deviation during the prediction of the material behaviour in case of biaxial loading [6]. Therefore, the applicability of the fitted model is required to be validated, which goal can be achieved by comparing the mechanical behaviour and thickness variation under biaxial load case.

In this paper, a punch-test based validation procedure is proposed via the case study of a thermoplastic microcellular polyethylene-terephthalate (MC-PET) foam material [4,5]. In the proposed method the thickness variation is investigated both experimentally and numerically, by means of laser scanning method and FE simulations, respectively. As a result, not only the thickness variation is obtained with great accuracy, but the comparison of the measured and FE results can also be applied for evaluating the model prediction.

The paper is organized as follows. The investigated MC-PET foam material and the constitutive model used in the simulation is summarized in Section 2. In Section 3, the novel validation method based on punch-tests and laser scanning measurement is presented including the detailed description of the experimental

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https://doi.org/10.1016/j.matpr.2020.02.977
2214-7853/
Selection and peer-review under responsibility of the scientific committee of the 36th Danubia Adria Symposium on Advances in Experimental Mechanics.

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setup. The comparison of the punch-test measurements and the FE simulation results are summarized in Section 4, while the main conclusions are presented in Section 5.

2. Investigated material and constitutive model

In this contribution a microcellular polyethylene-terephthalate foam (MC-PET) is investigated. This material is mainly applied in lighting applications (e.g. as lamp shells) due to its favourable diffuse reflection properties. The main manufacturing process of such parts is thermoforming, therefore there is significant need to develop an accurate material model on the entire temperature domain of the forming process, namely 21–210 °C.

2.1. Temperature-dependent mechanical behaviour

The mechanical behaviour of MC-PET materials has been investigated and analysed in detail in a recent contribution of the Authors [5]. The investigated MC-PET shows temperature-dependent behaviour, which can be demonstrated using cyclic uniaxial tests (see Fig. 1a). Furthermore, a significant change in the material behaviour was detected above the so-called glass transition temperature, which was found to be $T_g = 90$ °C according to the DMA measurement [5].

2.2. Constitutive model

A possible candidate for modelling such complex mechanical behaviour is the two-layer viscoplastic (TLVP) model family, which consists of a Maxwell-type nonlinear viscoelastic branch connected with an elastic–plastic part in parallel manner. The 1D representation of the TLVP model is depicted in Fig. 1/b. The elastic behaviour is characterised by the elastic modulus $E = E_V + E_P$ and the ratio of the fraction of elasticity $f = E_V/E$ (i.e. the ratio of the elastic contribution in the viscoelastic branch and the total elastic modulus). The yielding behaviour was modelled using associative flow rule based on the Mises yield criterion with linear isotropic hardening, while the corresponding material parameters are the initial yield stress σ_{Y0} and the plastic hardening modulus H. For the nonlinear viscous behaviour strain- and time-hardening power law models were applied. The governing equation of the creep strain rate in case of strain-hardening power-law model can be expressed as

$$\dot{\bar{\varepsilon}}^{cr} = \left(Aq^n[(m+1)\bar{\varepsilon}^{cr}]^m\right)^{\frac{1}{m+1}}, \tag{1}$$

where q represents the Mises-equivalent stress and $\bar{\varepsilon}^{cr}$ is the uniaxial equivalent creep strain, whereas A, n and m are material parameters [7,8]. For time-hardening power-law creeping the governing equation is expressed explicitly with the time t as [7,8].

$$\dot{\bar{\varepsilon}}^{cr} = Aq^n t^m. \tag{2}$$

The material model fitting process of such an advanced constitutive model is a challenging engineering task. A possible solution is to apply a FE-based fitting strategy to find the material parameters with respect to uniaxial test data at several temperatures [4,5]. In this contribution the temperature-dependent material parameters published in [5] are applied including 10 different temperature levels, namely 21, 60, 75, 83, 90, 97, 106, 120, 160 and 210 °C. As it was concluded in [5] the TLVP model using both strain- and time-hardening creeping was able to characterize the uniaxial behaviour with excellent accuracy (see Fig. 1c) at all temperatures.

3. Validation strategy

During thermoforming, the dominant loading is biaxial, therefore one cannot rely on the fitted model on uniaxial data without validation. In the literature a commonly applied method for performing such biaxial loading with single-column testing systems is punch-test measurements [9,10]. In our proposed method, punch-tests are combined with laser scanning measurements in order to obtain not only the force–displacement characteristic, but also the final shape and thickness variation along of the specimen. The measured punch-test data can further be utilized during the validation process by comparing with the FE-simulation result of the punch-test applying the fitted material model. The proposed validation method contains the following four main steps, which are also illustrated in Fig. 2:

1. Experimental punch-tests with spherical head geometry
2. 3D surface laser scanning of top and bottom surfaces
3. FE-simulation of the punch-test
4. Comparison of the thickness variation, final shape and force–time curves

3.1. Punch-tests

The schematics of the axisymmetric punch-test measurement is presented in Fig. 3a. A piece of a raw MC-PET material sheet with dimensions of 75 × 75 mm and thickness of 0.94 mm was placed in a special fixture mounted in Zwick Z010 Testing System

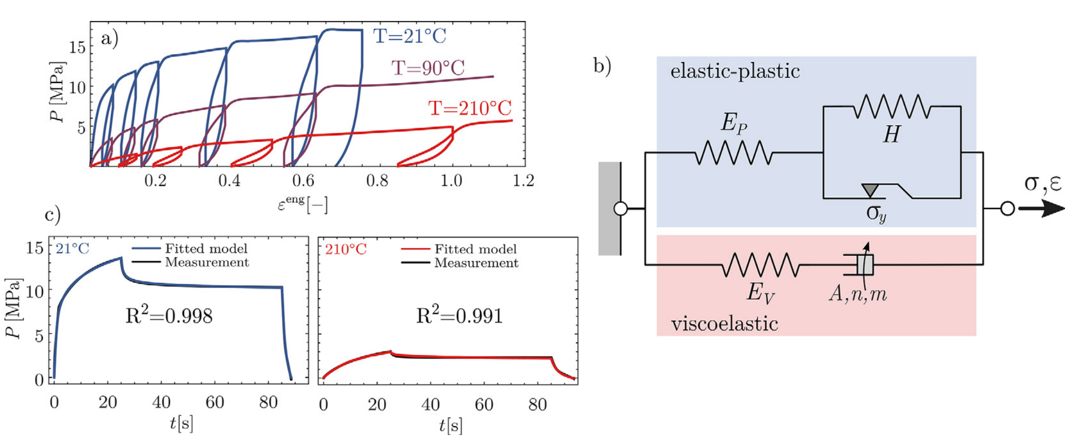

Fig. 1. a) The mechanical properties of the investigated MC-PET foam at different temperatures, b) the applied TLVP model and c) the results of the parameter fitting using TLVP models [5].

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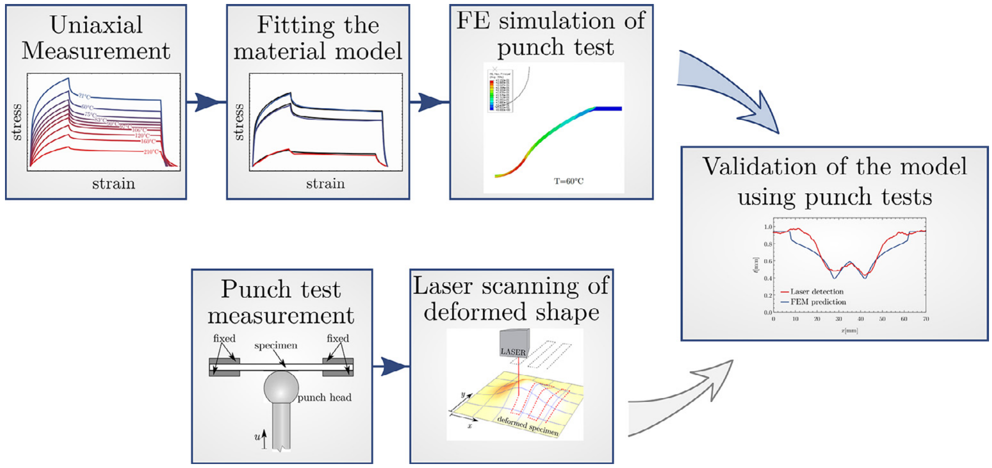

Fig. 2. The workflow of the validation strategy for thickness variation using punch-tests.

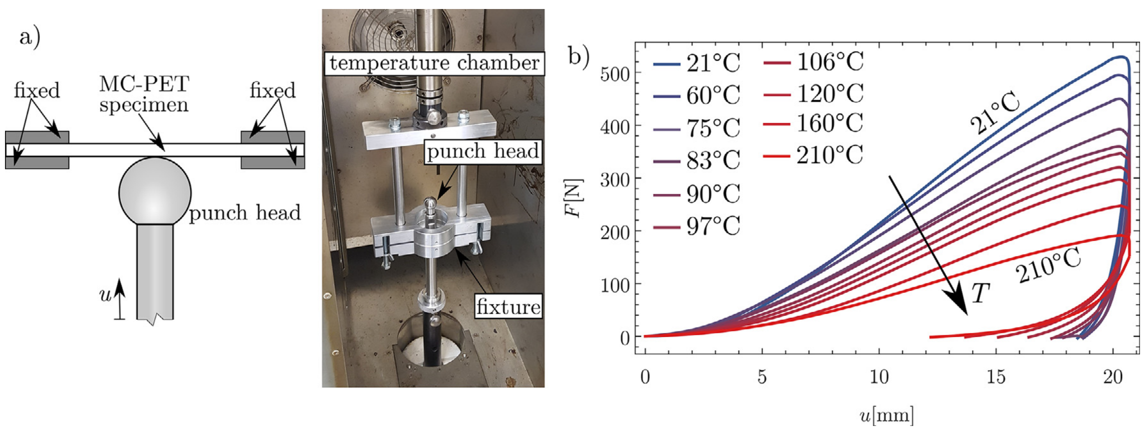

Fig. 3. a) The layout of the punch-test measurement in heat chamber and b) the measured force–displacement characteristics.

equipped with temperature chamber and the punch-test was performed with stainless steel spherical punch with diameter of 19 mm. The displacement-based loading consists of three parts: uploading with 500 mm/min, relaxation for 30 s and unloading with 100 mm/min until zero force is reached. Fig. 3b illustrates the experimental punch-test force–displacement ($F-u$) data at 10 different temperatures in the range of 21–210 °C.

3.2. Laser scanning

After punch-tests, the deformed specimens were placed in an NCT EmR-610Ms CNC milling machine, where the top and the bottom surfaces were scanned using a KEYENCE IL-030 Laser Differentiation Displacement Sensor following a predefined "zig-zag"-like path as shown in Fig. 4a (for further details of the laser system see [11]). After synchronization of the time signal of the distance variation recorded by the laser sensor and the position data provided by the CNC machine, the point clouds corresponding to both top and bottom surfaces of the deformed shape were obtained. Based on the scanned surfaces the thickness variation was determined along the surface and evaluated along x-axis by searching point P' on the top curve (see Fig. 4b) to corresponding point on the bottom curve (denoted by P). For this purpose, the perpendicular line e *to* the tangent at $P(x_P, y_P)$ was determined and then P' was obtained as the closest point on the top curve on the line. Finally, the thickness h at each x_P along the x-axis was obtained as

$$h(x_P) = \left|\overline{PP'}\right|. \quad (3)$$

3.3. FE simulation

As a next step, the FE simulation of the punch-test was performed using the commercial software ABAQUS [8]. The applied axisymmetric FE-model is illustrated in Fig. 4c. In order to reduce the computational time, the punch head was modelled as analytical rigid surface, while the contact between the rigid punch and the MC-PET was modelled with Coulomb-friction with coefficient of $\mu = 0.15$.

4. Results

The comparison of the measured punch-test force–time ($F-t$) data and the FE-simulation results are presented in Fig. 5. The comparison of the force–time curves shows that in case of 21 °C the discrepancy between the simulation result and the measurement is significant. However, at elevated temperatures this deviation becomes moderate, especially in case of TLVP model with time-hardening creeping. The variation of the thickness h along the x-axis shows good agreement with the results of the laser scanning measurement. The local minima on the thickness variation also indicate the contact region between the punch-head and the specimen. Finally, the excellent accuracy between the deformed geometries (represented with the position in z-direction) also confirms that the TLVP-model can be applied for describing the material behaviour in biaxial loading case as well.

In order to characterize the model accuracy with the temperature, the relative error of the maximal force and the minimal thick-

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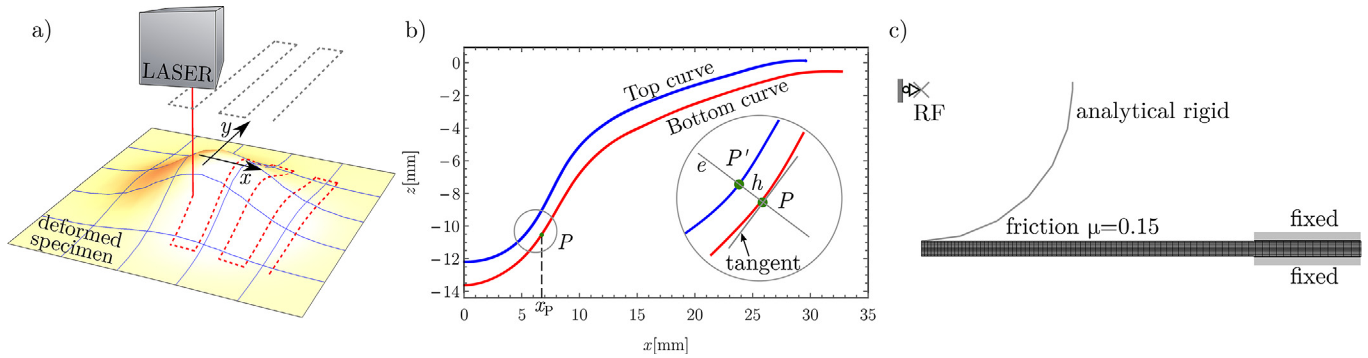

Fig. 4. a) Schematics of the deformed surface detection using laser scanner and b) the determination of local thickness from top and bottom curves and c) the applied FE model.

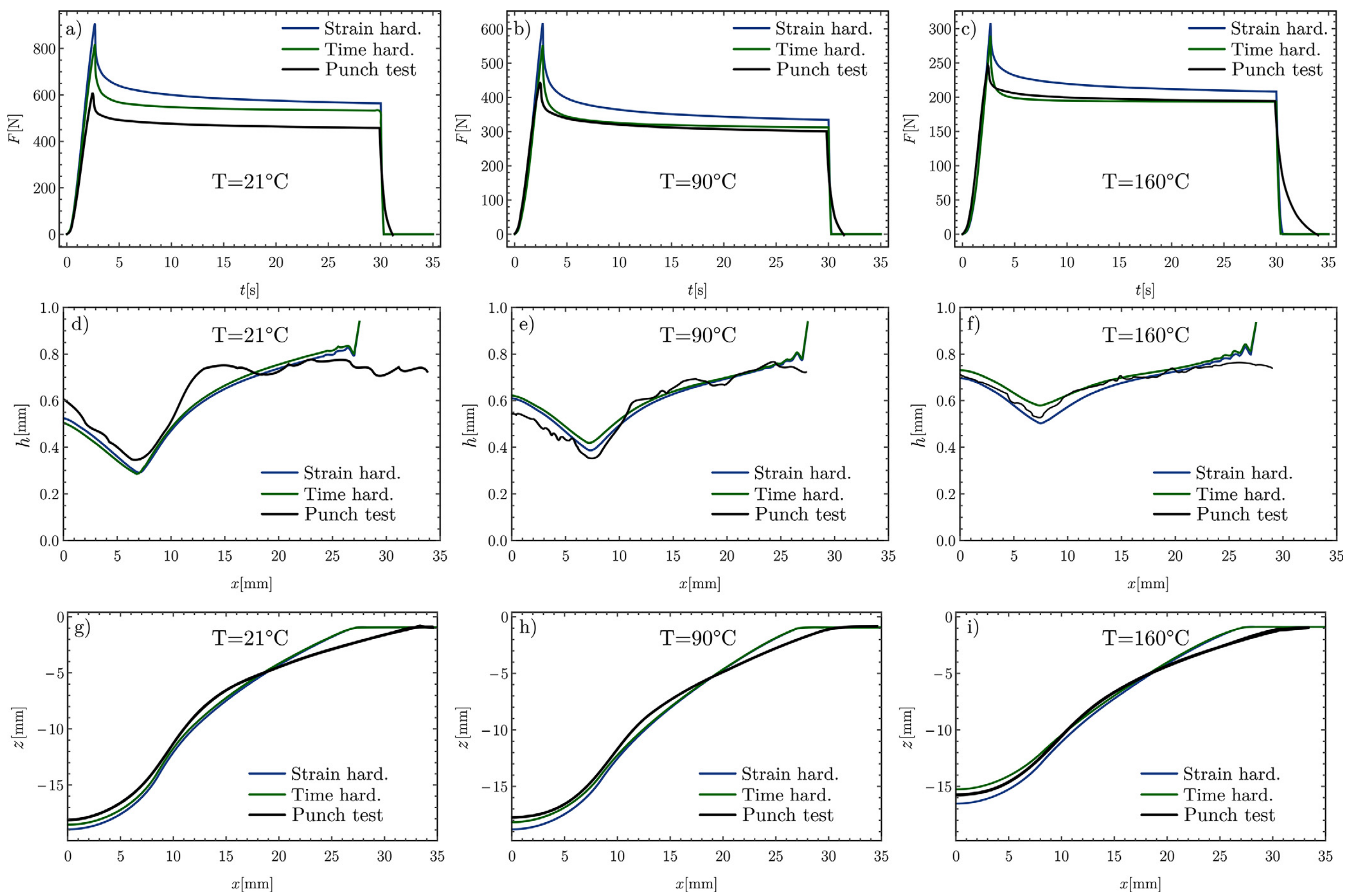

Fig. 5. The comparison of the experimental results and the FE simulation using TLVP with strain- and time-hardening power law models at 21 °C, 90 °C and 160 °C based on a)-c) force–time data from punch test, d)-f) thickness variation and g)-i) the deformed shape of the specimen by laser scanning technique.

ness values were compared using the measurement data as reference value. The variation of the relative errors δ_{rel} is illustrated in Fig. 6. The relative error of the maximal force varies between 5 and 30% and significantly decreases at high temperatures, while the error of the minimal thickness is always less than 10%.

5. Conclusion

In this paper, an experimental validation method was presented for thickness variation of thermoplastic materials using punch-tests and laser scanning technique, which can be applied for the evaluation of the fitted material models based on uniaxial measurements. Based on the case study of MC-PET foam material, the comparison of the thickness variation obtained by FE prediction and the laser scanning method are in good agreement. The relative error of the maximal force varies between 5 and 30% and significantly decreases at high temperatures, while the error of the minimal thickness is always less than 10%. The higher relative error of the maximal force values at low temperatures indicates that at these temperatures it is harder to extrapolate from uniaxial test data to biaxial load case. While at elevated temperatures the biaxial stress state can be approximated from the uniaxial test with better accuracy. The reason behind this fact might be that under

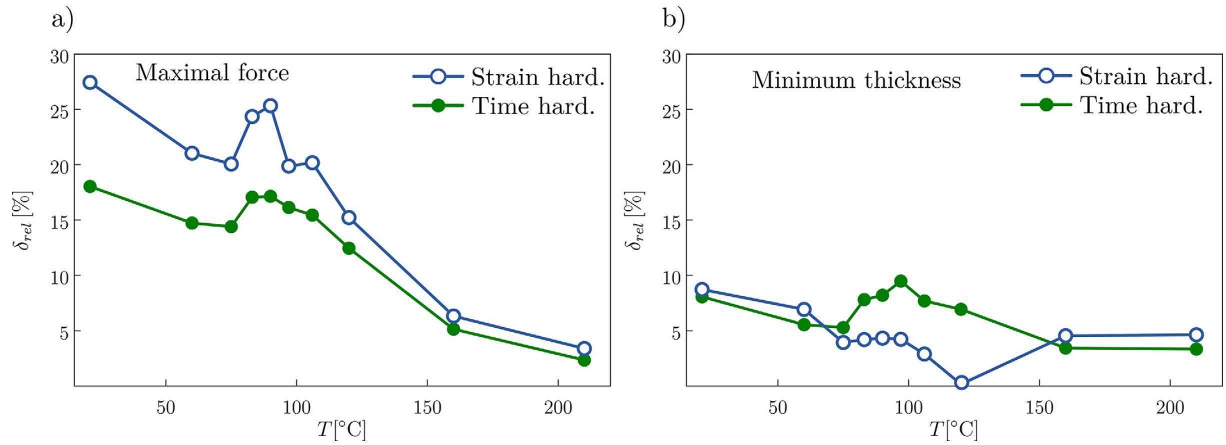

Fig. 6. Comparison of the error of the applied TLVP models with strain- and time-hardening power law models.

the glass transition temperature the material behaviour is mostly characterized by nonlinear elastic and yielding properties, while above this temperature the behaviour tends to be more fluid-like. It can also be concluded that the TLVP model can characterize the material behaviour in biaxial stress-state with adequate accuracy, even if only uniaxial tests were used during the fitting process. The results also revealed that the prediction of the TLVP model with time-hardening power law creeping is more accurate than TLVP model utilizing strain-hardening creeping law.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This research was supported by the János Bolyai Research Scholarship of the Hungarian Academy of Sciences. The research reported in this paper was supported by the Higher Education Excellence Program of the Ministry of Human Capacities in the frame of Nanotechnology research area of Budapest University of Technology and Economics (BME FIKP-NANO) and the National Talent Programme of the Ministry of Human Capacites, Hungary (NFTO-19-B-0053).

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