Detection of Defects in Plastic Products Using the Analysis of Noise In the Spectrum of Ultrasonic Bottom Signal

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Abstract: This article discusses the potential for detecting defects in plastic products using non-destructive quality control methods. Special attention is given to the quality of polyethylene containers for storing liquid mineral fertilizers. This issue is grounded in environmental and economic aspects. Therefore, the focus of scientific research is on quality control methods that ensure high reliability, waste reduction, workload optimization, and time savings. The authors conducted a literature review of non-destructive quality control methods for plastic products. Among the many traditional non-destructive methods, ultrasonic defect detection was chosen for this study. This choice is justified by the presence of specific identifying characteristics inherent to ultrasonic bottom signals, which provide higher accuracy and reliability in this context. One of these parameters is the noise coefficient (NN, r.u.a.), which affects the spectra of the ultrasonic bottom signal. Based on this parameter, it is possible to identify product defects related to the degree of sintering. It was found that samples with normal sintering have no noise, while samples with incomplete sintering show a noise level of 0.1 r.u.a. Thus, samples with incomplete sintering can be accurately identified through this parameter. This article demonstrates the potential use of ultrasonic quality control for polyethylene plastic products as a viable alternative to non-destructive quality control methods for products manufactured by rotational molding.

1 INTRODUCTION

Currently, a large number of companies are involved in the manufacturing of polyethylene (hereinafter PE) containers for storing liquid mineral fertilizers. One of the advanced manufacturing technologies for these products is Rotation Molding (RM). RM is a unique process that takes place at high temperatures, low pressure, and minimal shear force to produce hollow plastic items (Crawford, Throne, 2002; Ogila, Shao, Yang, Tan, 2017; Gupta, Ramkumar, Sangani, 2020). Products made from plastics in this way are known for their long service life, chemical resistance, and low cost (Hanana, Rodrigue, 2015; Vázquez Fletes, Cisneros López, Moscoso Sánchez, Mendizábal, González Núñez, Rodrigue, Ortega Gudiño, 2020; Crawford, 1996). In the initial stage of RM, raw material is distributed along the inner surface of the rotating mold, and simultaneous mold heating causes it to melt, forming a thin shell-like coating (Gibson, Shi, 1997; Adams, Jin, Barnes, Butterfield, Kearnes, 2021; Głogowska, Longwic, Ludziak, 2022; Nieschlag, Seuffert, Strack, Friedmann, Kärger, Henning, Fleischer, 2021). During the second stage of the process, liquid bridges form between the melted plastic particles, trapping micro air bubbles, which are supposed to disappear during the subsequent compaction stage, all at temperatures higher than the melting temperature of polyethylene (Spence, Crawford, 1996). If these micro air bubbles are not eliminated, the manufactured barrels will have low impact strength and other mechanical properties (Castellanos, Martin,

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Butterfield, McCourt, Kearns, Cassidy, 2020). Additionally, overheating the product (exceeding the allowable time in the oven) leads to thermo-oxidative degradation of PE and a significant deterioration of its mechanical properties. The impact strength of the finished containers for liquid mineral fertilizers (LMF) is the most important characteristic for assessing product quality. It is typically determined by the conditions of the manufacturing process and the composition of the raw materials being processed. Therefore, in the RM industry, there is a pressing need for precise control of the material sintering process, which is currently mainly monitored by tracking the Peak Internal Atmosphere Temperature (PIAT).

Due to the relatively high cost and detrimental consequences (for the environment, human health, and the company's reputation in case of container failure and excessive leakage of LMF into the soil and groundwater), the issue of 100% quality control of all LMF storage containers is highly relevant. Some manufacturers now use destructive testing to check one or two containers from each batch to maintain a high level of quality. This control process is inconvenient for two reasons. First, it is an expensive procedure. Second, there is a slight chance of producing a defective product due to critical equipment failure. In such cases, the product may be conditionally considered as high-quality, but it will, in reality, have significantly reduced mechanical properties (yield strength and impact resistance), which is often unacceptable. Therefore, to enhance the reliability, accuracy, and efficiency of quality control for PE products, it is necessary to employ non-destructive quality control methods.

In scientific literature, the following non-destructive methods for inspecting plastic components are distinguished:

1) Infrared method: Infrared spectroscopy/defectoscopy (hereafter referred to as IR) is described in numerous works (Anaya, de Paz, Rizzo-Sierra, Ramirez-Gutierrez, Isaza, 2022; Koinig, Friedrich, Rutrecht, Oreski, Barretta, Vollprecht, 2022; Neo, Low, Goodship, Debattista, 2023; Mite-Guzmán, Lazo, Triguero, Damián, Adrián, Perugachi, Vera-Villalobos, Rigail-Cedeño, 2023; Mazzoleni, Magni, Tretola, Luciano, Ferrari, Bernardi, Lin, Ottoboni, Binelli, Pinotti, 2023; Erchiqui, Kaddami, Dituba-Ngoma, Slaoui-Hasnaoui, 2020; Kroell, Chen, Küppers, Lorenzo, Maghmoumi, Schlaak, Thor, Nordmann, Greiff, 2023; Zhu, Chen, Wang, Guo, Lei, Jin, 2019; Gulmine, Janissek, Heise, Akcelrud, 2003). IR methods are based on the detection of infrared radiation reflected or transmitted through the examined plastic part. The ability to detect material defects relies on the relationship between the optical density of the material being examined and the intensity of the transmitted radiant energy. Such tests are well-suited for identifying internal cracks, lack of fusion, and voids with a diameter of about a millimeter or more.

2) X-ray method or X-ray computed tomography (hereafter referred to as CT): The use of X-ray methods in plastic and polymer research is described in works (Tominaga, Takeda, Kotera, Suzuki, Matsumoto, 2022; Zanini, Carmignato, 2022; Girard-Perier, Marque, Dupuy, Claeys-Bruno, Gaston, Dorey, Fifield, Ni, Li, Fuchs, Murphy, Pillai, Pharr, Nichols, 2022; Leonard, Fifield, Staack, Suresh, Pillai, McCoy, Faucette, Tucker, Huang, Md Kamrul, Perkins, Cooley, Murphy, 2021; Cramez, Oliveira, Fakirov, James, Crawford, Apostolov, Krumova, 2001; Xie, Zhao, Jing, Zhang, Xia, Fu, 2018; Cramez, Oliveira, Fakirov, Crawford, Apostolov, Krumova, 2001). This control method involves passing X-ray radiation through examined plastics with various structures or defects. CT can detect non-sintered defects in PE components thanks to the registration of "microbubbles."

3) Capillary methods: The application of capillary control methods for the examination of plastics is described in works (Lopatin, 2019; Kuznetsov, Ivanchik, 2021). They are used to detect all types of surface cracks, delaminations, leaks in welded structures made of plastic materials. Capillary methods include fluorescent, color (paint method), and fluorescent-color.

4) Radiofrequency methods: Radiofrequency control methods (based on the use of radio waves in the extremely high-frequency range from 1 to 100 GHz) are used to detect certain defects in plastic components (Katagiri, Chen, Yusa, Hashizume, 2021; Zou, Sneed, Mirala, Al Qaseer, Donnell, 2023; Wahab, Md Maniruzzaman, Mohd. Sam, Kok, Bhatti, Khairul, 2019). The positive aspect of this method is that radio waves in this spectral range penetrate and propagate very well in plastics (as well as in other dielectrics). In this case, there is no need for contact between the radio wave emitting devices and the plastic component. In the presence of cracks, foreign inclusions, and other defects in plastic components, radio waves, when reflected or passing through them, change their phase (phase method), amplitude (amplitude method), or polarization characteristics (polarization method).

5) Electrostatic method: The electrostatic method, like capillary methods, allows the detection of surface defects (cracks, pores, non-uniformities, etc.) in welded plastic joints (Brühl, Hanke, Pidcock, 2001; Esmaeili, Wang, Harvey, White, Holweger, 2023; Esmaeili, Zuercher, Wang, Harvey, Holweger, White, Schlücker, 2018). This method is simple,

inexpensive, and highly productive. However, this method is effective only for detecting cracks or surface defects in PE products, and it cannot be used to identify subsurface and non-sintered defects.

6) Thermal method: The thermal control method is based on the alteration of the distribution of thermal radiation passing through the examined item in the presence of a defect (Melnikov, Sivagurunathan, Guo, Tolev, Mandelis, Ly, Lawcock, 2016; Maldague, Krapex, Cielo, Poussart, 1998; Dolinko, Kaufmann, 2007; Vavilov, DeGiovanni, Didierjean, Maillet, Sengoulier, Houlbert, 1993). It is used to inspect sheet welded plastic joints after the removal of the sprue. This method allows for the determination of the shape, dimensions, and locations of large defects such as "integrity violations."

7) Raman Spectroscopy: Spectroscopy of Raman scattering of light (hereafter referred to as Raman) has been used to detect microscopic structural changes in PE HP/LD due to ultraviolet radiation in works (Yusuke, Takumitsu, Kento, Toshio, Kohhei, 2018; Yusuke, Takumitsu, Kento, Toshio, Kohhei, 2018; Mousavi, Ahmadi, Arabi, 2022; Jin, Song, Ma, Li, Li, Zhang, 2022). Under the influence of degradation phenomena, the proportion of non-crystalline sequential trans-chains sharply decreases after approximately 600 hours, along with a decrease in molecular weight and an increase in crystallinity.

8) Magnetic Levitation: Magnetic levitation is also used as a non-destructive method for diagnosing plastic items (Xia, Zhao, Xie, Zhang, Fu, Turng, 2018; Shi, Gao, Ullah, Li, Wang, Yang, 2016; Sekar, Roopmani, Krishnan, 2018; Landrigan, Li, Turnbull, Burr, Niebur, Roeder, 2011; Chen, Turng, 2005; Yang, Zhao, Zhou, Chen, 2014; van Dongen, Desai, Orr, Baker, Holl, 2013; Zhao, Fu, Zhou, Cui, 2011; Lee, An, Chua, 2017; Tang, Zhao, Shen, Zhou, Xie, Fu, 2020). Magnetic levitation can be used to detect shrinkage voids caused by the presence of microbubbles in polyethylene items. The degree of porosity in plastic parts can be calculated using magnetic levitation because voids caused by shrinkage affect density (Tang, Zhao, Shen, Zhou, Xie, Fu, 2020).

9) Ultrasonic Defect Inspection: Ultrasonic defect inspection is a collection of non-destructive control methods that use ultrasonic waves to detect defects in plastic items (Lee, Jeon, Lee, 2023; Righi, Li, Jiang, Li, Tian, 2022; Cheng, Ma, Wu, Zu, Hu, 2023; Fatin, bin Ismail, bin Mohd Aris, 2023; Jung, Kang, Song, Lee, Jeon, 2022; Honarvar, Varvani-Farahani, 2020; Wu, Huang, Krishnaswamy, 2017; Huang, Turner, Song, Ni, Li, 2019). The obtained data are then analyzed to determine the shape, size, depth, and other characteristics of defects. With advantages such as sensitivity to damage, high efficiency, a wide detection range, and a long propagation distance (Hong, Su, Lu, Sohn, Qing, 2015), it is widely used for non-destructive control of composite materials, metals, ceramics, and other structures (Su, Hong, 2016; Behravan, deJong, Brand, 2021).

From all the various non-destructive control methods for plastic items discussed above (described in scientific literature and databases such as "Scopus" and "Web of Science"), the most optimal method in terms of quality, speed, and accuracy of assessing the quality of plastic items produced by rotational molding is the ultrasonic method (hereafter referred to as UT).

In works (Gaisin, Tyukanko, Demyanenko, 2021; Gaisin, Tyukanko, 2020), ultrasonic testing (UT) of PE parts produced by rotational molding was studied. This method, implemented using the USW-60 defectoscope, involves transmitting a probing ultrasonic signal through close contact with the plastic's contact surface. The reflected bottom signal, representing a radio pulse with frequency deviation, carries several informative parameters: the thickness of the item, the speed of the ultrasonic signal's propagation, and its amplitude. However, due to the equivalence of amplitude in the bottom signal for both normal and overcooked samples, it is not possible to determine the branching of chains and the formation of cross-links between crystallites, characteristics of thermo-oxidative degradation.

In works (Gomes, Thompson, 2017; Gomes, Thompson, 2018; Gomes, Garg, Mhaskar, Thompson, 2019), the authors presented the possibility of detecting product defects related to NS and TDS. However, there is a significant margin of error in determining the quality of items in these results, and the model's adequacy varies from 58.6% to 80.3%.

In work (Tyukanko, Demyanenko, Semenyuk, Dyuryagina, Alyoshin, Tarunin, Voropaeva, 2023), the authors examined the influence of temperature, plastic thickness, PIAT on the speed, amplitude of the bottom signal, the temperature stability coefficient, and the third harmonic coefficient using Taguchi methods (Tyukanko, Demyanenko, Dyuryagina, Ostrovnoy, Lezhneva, 2021) and probabilistic-deterministic planning (Gomes, Thompson, 2017; Gomes, Thompson, 2018; Gomes, Garg, Mhaskar, Thompson, 2019; Tyukanko, Demyanenko, Semenyuk, Dyuryagina, Alyoshin, Tarunin, Voropaeva, 2023; Dyuryagina, Lutsenko, Tyukanko, 2019; Dyuryagina, Lutsenko, Ostrovnoy, Tyukanko, Demyanenko, Akanova, 2022; Dyuryagina, Lutsenko, Demyanenko, Tyukanko, Ostrovnoy, Yanevich, 2022; Tyukanko, Duryagina, Ostrovnoy, Demyanenko, 2017; Ostrovnoy, KDyuryagina, Demyanenko, Tyukanko, 2021; Tyukanko, Demyanenko, Dyuryagina, Ostrovnoy, Lezhneva,

2021; Tyukanko, Demyanenko, Dyuryagina, Ostrovnoy, Aubakirova, 2022; Zhanibekov, Brilkov, 2023). As a result, it was established that the third harmonic coefficient allows for the detection of defects with high precision (up to 95%). Works (Gomes, Thompson, 2017; Gomes, Thompson, 2018; Gomes, Garg, Mhaskar, Thompson, 2019; Tyukanko, Demyanenko, Semenyuk, Dyuryagina, Alyoshin, Tarunin, Voropaeva, 2023; Dyuryagina, Lutsenko, Tyukanko, 2019; Dyuryagina, Lutsenko, Ostrovnoy, Tyukanko, Demyanenko, Akanova, 2022; Dyuryagina, Lutsenko, Demyanenko, Tyukanko, Ostrovnoy, Yanevich, 2022; Tyukanko, Duryagina, Ostrovnoy, Demyanenko, 2017; Ostrovnoy, KDyuryagina, Demyanenko, Tyukanko, 2021; Tyukanko, Demyanenko, Dyuryagina, Ostrovnoy, Lezhneva, 2021; Tyukanko, Demyanenko, Dyuryagina, Ostrovnoy, Aubakirova, 2022; Zhanibekov, Brilkov, 2023) did not investigate the impact of one important spectral parameter, such as the noise coefficient (NN). This article conducts an experiment to explore the possibility of identifying defects related to incomplete sintering of polyethylene plastic using noise analysis in the spectrum of the bottom ultrasonic signal.

2 MATERIALS AND METHODS

2.1 Materials

For the research, rotational polyethylene (LLDPE) "ELTEX HD3850UA" hexene (hereinafter referred to as "ELTEX") with a density of 9381 kg/m³ and a melt flow index (MFI) of 0.0044 kg/10 min at (190 °C/2.16 kg) from INEOS (London, UK) was used.

2.2 Sample Preparation

During ultrasonic testing of the samples, the noise coefficient (NN, r.u.a) was determined using the shadow mirror method. Industrial ultrasonic flaw detector UCD 60 by Kropus (Russia) was used in the research. Prior to the experiments, a layer of glycerin was applied to the surface of the plastic sample to improve the transmission of the ultrasonic signal. The shadow mirror method involves the use of two piezoelectric sensors, one of which functions as a transmitter, and the other as a receiver. A signal with an amplitude of 200 V, a fill frequency of 3.75 MHz, and a pulse repetition frequency of 20 Hz is emitted at an angle of 65 degrees, and the bottom signal is detected on the receiving side. Using the "Spectrum" function on the instrument's scale, the relative level of amplitude harmonics and noise can be determined. The amplitude step of the grid is 0.1 r.u.a. (relative unit of amplitude).

3 RESULTS

Fig. 1 presents the spectrum of the bottom ultrasonic signal for Eltex polyethylene with a normal degree of sintering (NS) at a temperature of 20°C and PIAT 200°C. Fig. 2 demonstrates the graph of the ultrasonic signal under similar temperature conditions, but for polyethylene plastic with incomplete sintering, which is identified as a product defect.

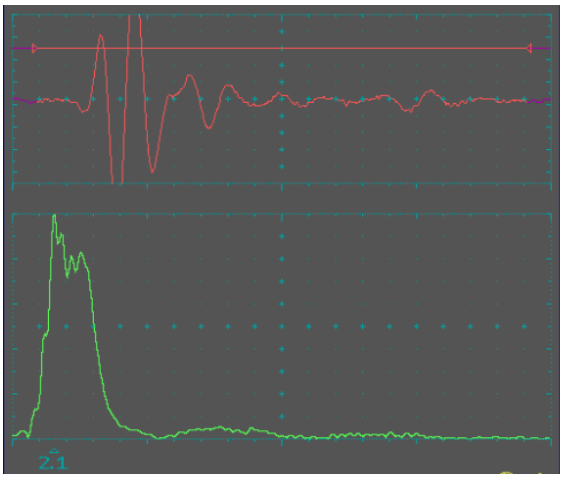

Figure 1: The spectrum of the bottom ultrasonic signal for Eltex plastic with a sintering degree of NS, temperature 20°C, and PIAT 200°C.

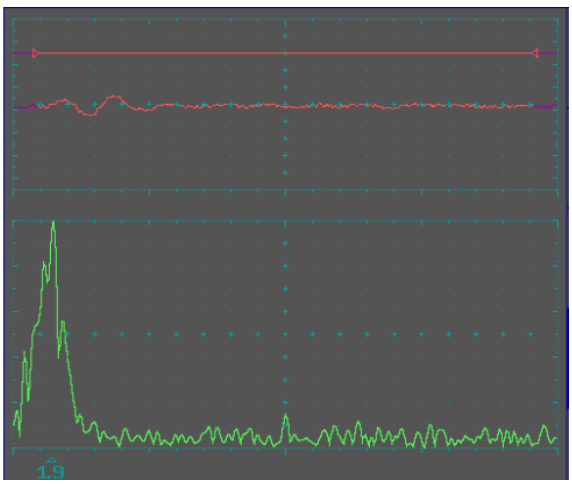

Figure 2: The spectrum of the bottom ultrasonic signal for Eltex plastic with a sintering degree of ICS, temperature 20°C, and PIAT 170°C.

4 CONCLUSIONS

The spectra of the bottom ultrasonic signal are directly dependent on PIAT. Using two samples with different PIAT values (NS and ICS), it was observed that in the NS sample, there is an absence of noise, and the third harmonic with an amplitude of 0.05 is evident. Meanwhile, in the ICS sample, the noise level reaches 0.1 r.u.a. Based on the above, it can be concluded that ultrasonic testing (particularly using the shadow mirror method) for PE allows for the non-destructive detection of product defects related to its sintering, ensuring the quality control of the finished product.

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REFERENCES

Crawford, R.J., Throne, J.L., 2002. Rotational Molding Technology, William Andrew Publishing: New York, NY, USA.

Ogila, K.O., Shao, M., Yang, W., Tan, J., 2017. Rotational molding: A review of the models and materials. *Express Polym. Lett.* 11, 778–798.

Gupta, N., Ramkumar, P.L., Sangani, V., 2020. An approach toward augmenting materials, additives, processability and parameterization in rotational molding: A review. *Mater. Manuf. Process.* 35, 1539–1556.

Hanana, F.E., Rodrigue, D., 2015. Rotational molding of polymer composites reinforced with natural fibers. *Plast. Eng.* 71, 28–31.

Vázquez Fletes, R.C., Cisneros López, E.O., Moscoso Sánchez, F.J.,Mendizábal, E., González Núñez, R.,Rodrigue, D., Ortega Gudiño, P., 2020. Morphological and mechanical properties of bilayers wood–plastic composites and foams obtained by rotational molding. *Polymers* 12, 503.

Crawford, R.J., 1996. Recent advances in the manufacture of plastic products by rotomoulding. *J. Mater. Process*, 56, 263–271.

Gibson, I., Shi, D., 1997. Material properties and fabrication parameters in selective laser sintering process. *Rapid Prototyping Journal*, 3(4):129–136.

Adams, J., Jin, Y., Barnes, D., Butterfield, J., Kearnes, M., 2021. Motion control for uniaxial rotational molding. *Journal of Applied Polymer Science* Volume 138, Issue 8, 20.

Głogowska, K., Longwic, F., Ludziak, K., 2022. Effect of mould speed on selected properties of moulded parts and energy consumption in rotational moulding. *Bulletin of the Polish Academy of Sciences: Technical Sciences*

Nieschlag, J., Seuffert, J., Strack, D., Friedmann, M., Kärger, L., Henning, F., Fleischer, J., 2021. Experimental and Numerical Analysis of Mold Filling in Rotational Molding. *J. Compos. Sci.* 5, 289.

Spence, A.G., Crawford, R. J., 1996. The effect of processing variables on the foRMation and removal of bubbles in rotationally molded products. *Polymer Engineering & Science*, 36(7):993–1009.

Castellanos, D., Martin, P.J., Butterfield, J., McCourt, M., Kearns, M., Cassidy, P., 2020. Sintering and densification of fibre reinforcement in polymers during rotational moulding (Conference Paper) 23rd International Conference on Material FoRMing, ESAFORM 2020, Cottbus, GeRMany. Volume 47, 2020, Pages 980–986

Anaya, K., de Paz, J.-P.-Z., Rizzo-Sierra, J.A., Ramirez-Gutierrez, C.F., Isaza, C., 2022. Extended hyperspectral characterization of plastic automotive parts via Acousto-optic Tunable Filter and Fourier Transform Infrared Spectrometry. *Infrared Physics & Technology*, Volume 127, 104402.

Koinig, G., Friedrich, K., Rutrecht, B., Oreski, G., Barretta, C., Vollprecht, D., 2022. Influence of reflective materials, emitter intensity and foil thickness on the variability of near-infrared spectra of 2D plastic packaging materials. *Waste Management*, Volume 144, Pages 543-551.

Neo, E.R.K., Low, J.S.C., Goodship, V., Debattista, K., 2023. Deep learning for chemometric analysis of plastic spectral data from infrared and Raman databases. *Resources, Conservation and Recycling*, Volume 188, 2023, 106718.

Mite-Guzmán, N., Lazo, M., Triguero, J., Damián, A., Adrián,E., Perugachi, R., Vera-Villalobos, J., Rigail-Cedeño, A., 2023. Two-dimensional infrared for monitoring the structural variations of UV-aged recycled polypropylene straps used in the Ecuadorian banana industry. *Case Studies in Chemical and Environmental Engineering*, Volume 7, 100359.

Mazzoleni, Sh., Magni, S., Tretola, M., Luciano, A., Ferrari, L., Bernardi, C.E.M., Lin, P., Ottoboni, M., Binelli, A., Pinotti, L., 2023. Packaging contaminants in former food products: Using Fourier Transform Infrared Spectroscopy to identify the remnants and the associated risks, *Journal of Hazardous Materials*, Volume 448, 130888.

Erchiqui, F., Kaddami, H., Dituba-Ngoma, G., Slaoui-Hasnaoui, F., 2020. Comparative study of the use of infrared and microwave heating modes for the thermoforming of wood-plastic composite sheets. *International Journal of Heat and Mass Transfer*, Volume 158, 119996.

Kroell, N., Chen, X., Küppers, B., Lorenzo, J., Maghmoumi, A., Schlaak, M., Thor, E., Nordmann, C., Greiff, K., 2023. Near-infrared-based determination of mass-based material flow compositions in mechanical recycling of post-consumer plastics: Technical feasibility enables novel applications. *Resources, Conservation and Recycling*, Volume 191.106873.

Zhu, Sh., Chen, H., Wang, M., Guo, X., Lei, Y., Jin, G., 2019. Plastic solid waste identification system based on near infrared spectroscopy in combination with support vector machine. *Advanced Industrial and Engineering Polymer Research*, Volume 2, Issue 2, 2019, Pages 77-81.

Gulmine, J. V., Janissek, P. R., Heise, H. M., Akcelrud, L., 2003. Degradation profile of polyethylene after artificial accelerated weathering. *Polymer Degradation and Stability*, 79(3):385–397.

Tominaga, R., Takeda, Y., Kotera, M., Suzuki, Y., Matsumoto, A., 2022. Non-destructive observation of internal structures of epoxy monolith and co-continuous network polymer using X-ray CT imaging for elucidation of their unique mechanical features and fracture mechanism. *Polymer*, Volume 263, 2022, 125433.

Zanini, F., Carmignato, S., 2022. Reference object for traceability establishment in X-ray computed tomography measurements of fiber length in fiber-reinforced polymeric materials. *Precision Engineering*, Volume 77, 2022, Pages 33-39.

Girard-Perier, N., Marque, S., Dupuy, N., Claeys-Bruno, M., Gaston, F., Dorey, S., Fifield, L., Ni, Y., Li, D., Fuchs, W., Murphy, M., Pillai, S., Pharr, M., Nichols, L., 2022. Effects of X-Rays, Electron Beam, and Gamma Irradiation on Chemical and Physical Properties of EVA Multilayer Films. *Frontiers in Chemistry.* 10.

Leonard, S. Fifield, M.Ph., Staack, D., Suresh, D., Pillai, L.N., McCoy, J., Faucette, T., Tucker, T. B., Huang, M., Md Kamrul, H., Perkins, L., Cooley, S. K., Murphy, M.K., 2021. Direct comparison of gamma, electron beam and X-ray irradiation effects on single-use blood collection devices with plastic components, Radiation Physics and Chemistry, Volume 180, 2021, 109282.

Cramez, M.C., Oliveira, M.J., Fakirov, S., James, R., Crawford, A., Apostolov, A., Krumova, M., 2001. Rotationally molded polyethylene: Structural characterization by x-ray and microhardness measurements. *Advances in Polymer Technology*, 20(2):116–124..

Xie, J., Zhao, P., Jing, Zh., Zhang, Ch., Xia, N., Fu, J., 2018. Research on the sensitivity of magnetic levitation (MagLev) devices. *Journal of Magnetism and Magnetic Materials*, Volume 468, 2018, Pages 100-104.

Cramez, M., Oliveira, M., Fakirov, S., Crawford, R., Apostolov, A., Krumova, M., 2001. Rotationally molded polyethylene: Structural characterization by X-ray and microhardness measurements. *Advances in Polymer Technology.* 20. 116 - 124.

Lopatin, V., 2019. Improving the capillary method of non-destructive testing. *Methods and devices of quality control.* 33-38.

Kuznetsov, A., Ivanchik, S., 2021. Flaw detection of ship equipment parts. *Journal of Physics: Conference Series.* 2131. 052059.

Katagiri, T., Chen, G., Yusa, N., Hashizume, H., 2021. Demonstration of detection of the multiple pipe wall thinning defects using microwaves. *Measurement*, Volume 175, 109074.

Zou, X., Sneed, L.H., Mirala, A., Al Qaseer, M.T., Donnell, K., 2023. Debonding detection of defected CFRP-concrete interface using active microwave thermography, Composite Structures, Volume 310, 2023, 116753.

Wahab, A., Md Maniruzzaman, A. A., Mohd. Sam, A.R., Kok, Y.Y., Bhatti, A.Q., Khairul, A.K., 2019. Review on microwave nondestructive testing techniques and its applications in concrete technology. *Construction and Building Materials*, Volume 209, 2019, Pages 135-146.

Brühl, M., Hanke, M., Pidcock, M., 2001. Crack detection using electrostatic measurements. M2AN. Mathematical Modelling and Numerical Analysis. *ESAIM, European Series in Applied and Industrial Mathematics*. 35.

Esmaeili, K., Wang, L., Harvey, T., White, N., Holweger, W., 2023. A Study on the Influence of Electrical Discharges on the Formation of White Etching Cracks in Oil-Lubricated Rolling Contacts and Their Detection Using Electrostatic Sensing Technique. *Lubricants.* 11. 164.

Esmaeili, K., Zuercher, M., Wang, L., Harvey, T., Holweger, W., White, N., Schlücker, E., 2018. A study of white etching crack bearing failure detection using electrostatic sensing in wind turbine gearboxes. *International Journal of Condition Monitoring*. 8. 82-88.

Melnikov, A., Sivagurunathan, K., Guo, X., Tolev, J., Mandelis, A., Ly, K., Lawcock, R., 2016. Non-destructive thermal-wave-radar imaging of manufactured green powder metallurgy compact flaws (cracks). *NDT & E International*, Volume 86, 2017, Pages 140-152.

Maldague, X., Krapex, J.C., Cielo, P., Poussart, D., 1998. Processing of thermal images for the detection and enhancement of subsurface flaws in composite materials: Signal Processing and Pattern Recognition in Nondestructive Evaluation of Materials, Proceedings of the NATO Advanced Research Workshop, Lac Beauport, Quebec, Canada, 19–22 Aug. 1987. Edited by C.M. Chen, pp. 257–286. NDT & E International, Volume 26, Issue 2, 1993, Page 105.

Dolinko, A. E., Kaufmann, G. H., 2007. Enhancement in flaw detectability by means of lockin temporal speckle pattern interferometry and thermal waves. *Optics and*

Lasers in Engineering, Volume 45, Issue 6, 2007, Pages 690-694.

Vavilov, V.P., DeGiovanni, A., Didierjean, S., Maillet, D., Sengoulier, A.A., Houlbert, A.-S., 1993. Thermal flaw detection and tomography of carbon fiber-reinforced plastic articles. *Soviet Journal of Nondestructive Testing*, Vol. 27, No. 9, pp. 609–619 (May 1992), NDT & E International, Volume 26, Issue 2, 1993, Page 101.

Yusuke, H., Takumitsu, K., Kento, T., Toshio, I., Kohhei, N., 2018. Microscopic structural changes during photodegradation of low-density polyethylene detected by Raman spectroscopy. Polymer Degradation and Stability,150:67–72.

Yusuke, H., Takumitsu, K., Kento, T., Toshio, I., Kohhei, N., 2018. Microscopic structural changes during photodegradation of low-density polyethylene detected by Raman spectroscopy. *Polymer Degradation and Stability*, Volume 150, Pages 67-72.

Mousavi, H., Ahmadi, Sh., Arabi, H., 2022. Mixing of hindered amine-grafted polyolefin elastomers with LDPE to enhance its long-term weathering and photo-stability. Polymer Degradation and Stability. 198. 109882.

Jin, N., Song, Y., Ma, R., Li, J., Li, G., Zhang, D., 2022. Characterization and identification of microplastics using Raman spectroscopy coupled with multivariate analysis. *Analytica Chimica Acta.* 1197.

Xia, N., Zhao, P., Xie, J., Zhang, Ch., Fu, J., Turng, L/-S., 2018. Defect diagnosis for polymeric samples via magnetic levitation, NDT & E International, Volume 100, 2018, Pages 175-182.

Shi, Z., Gao, X.J., Ullah, M.W., Li, S., Wang, Q., Yang, G., 2016. Electroconductive natural polymer-based hydrogels. *Biomaterial*s, 111, 40-54 .

Sekar, M.P., Roopmani, P., Krishnan, U.M., 2018. Development of a novel porous polyvinyl formal (PVF) microfibrous scaffold for nerve tissue engineering. *Polymer*, 142, 170-182.

Landrigan, M.D., Li, J., Turnbull, T.L., Burr, D.B., Niebur, G.L., Roeder, R.K., 2011. Contrast-enhanced micro-computed tomography of fatigue microdamage accumulation in human cortical bone. *Bone*, 48 3, 443-50.

Chen, Z., Turng, L., 2005. A review of current developments in process and quality control for injection molding. *Advances in Polymer Technology*, 24, 165-182.

Yang, D., Zhao, P., Zhou, H., Chen, L., 2014. Computer determination of weld lines in injection molding based on filling simulation with surface model. *Journal of Reinforced Plastics and Composites*, 33, 1403 - 1415.

van Dongen, M.A., Desai, A.M., Orr, B.G., Baker, J.R., Holl, M.M., 2013. Quantitative analysis of generation and branch defects in G5 poly(amidoamine) dendrimer. *Polymer*, 54 16, 4126-4133.

Zhao, P., Fu, J., Zhou, H., Cui, S., 2011. Automated process parameters tuning for an injection moulding machine with soft computing. *Journal of Zhejiang University-SCIENCE A*, 12, 201-206.

Lee, J., An, J., Chua, C.K., 2017. Fundamentals and applications of 3D printing for novel materials. *Applied Materials Today*, 7, 120-133.

Tang, T., Zhao, P., Shen, Ya., Zhou, H., Xie, J., Fu,J., 2020. Detecting shrinkage voids in plastic gears using magnetic levitation, Polymer Testing, Volume 91, 2020, 106820.

Lee, K.-J., Jeon, M.-S., Lee, J.-R., 2023. Evaluation of manufacturing defects in 3D printed carbon fiber reinforced cylindrical composite structure based on laser ultrasonic testing, NDT & E International, Volume 135.

Righi, H., Li, T., Jiang, Zh., Li, J., Tian, Zh., 2022. Numerical Study of Ultrasonic Guided Waves in a Composite-Plastic Lap Joint, IFAC-PapersOnLine, Volume 55, Issue 27, 2022, Pages 353-357.

Cheng, X., Ma, G., Wu, Zh., Zu, H., Hu, X., 2023. Automatic defect depth estimation for ultrasonic testing in carbon fiber reinforced composites using deep learning. *NDT & E International*, Volume 135.

Fatin, Sh. N., bin Ismail, M.N., bin Mohd Aris, K.D., 2023. Measuring material velocity and thickness mapping of flax fiber-reinforced plastic composites using automated ultrasonic rapid motion scanner. *Materials Today: Proceedings*, Volume 74, Part 3, 2023, Pages 419-424.

Jung, Ch., Kang, Y., Song, H., Lee, M.G., Jeon, Y., 2022. Ultrasonic fatigue analysis of 3D-printed carbon fiber reinforced plastic. *Heliyon*, Volume 8, Issue 11.

Honarvar, F., Varvani-Farahani, A., 2020. A review of ultrasonic testing applications in additive manufacturing: Defect evaluation, material characterization, and process control. *Ultrasonics*, Volume 108.

Wu, B., Huang, Y., Krishnaswamy, S., 2017. A Bayesian approach for sparse flaw detection from noisy signals for ultrasonic NDT. *NDT & E International*, Volume 85, Pages 76-85.

Huang, Y., Turner, J.A., Song, Y., Ni, P., Li, X., 2019. Enhanced ultrasonic detection of near-surface flaws using transverse-wave backscatter. *Ultrasonics*, Volume 98, . Pages 20-27.

Hong, M., Su, Zh., Lu, Y., Sohn, H., Qing, X., 2015. Locating fatigue damage using temporal signal features of nonlinear Lamb waves. *Mechanical Systems and Signal Processing*,Volumes 60–61, Pages 182-197.

Su, Z., Hong, M., 2016. 13 - Nonlinear ultrasonics for health monitoring of aerospace structures using active sparse sensor networks, Editor(s): Fuh-Gwo Yuan, Structural Health Monitoring (SHM) in Aerospace Structures, *Woodhead Publishing*, 2016, Pages 353-392.

Zima, B., Rucka, M., 2016. Guided waves for monitoring of plate structures with linear cracks of variable length. *Archives of Civil and Mechanical Engineering*, Volume 16, Issue 3, 2016, Pages 387-396..

Caggiano, A., Nele, L., 2018. Comparison of drilled hole quality evaluation in CFRP/CFRP stacks using optical

and ultrasonic non-destructive inspection. *Machining Science and Technology*. 22. 865-880.

Khodayar, F., López, F., Ibarra-Castanedo, C., Maldague, X., 2017. Optimization of the Inspection of Large Composite Materials Using Robotized Line Scan Thermography. *Journal of Nondestructive Evaluation.*

Zhang, B., Hong, X., Liu, Y., 2021. Distribution adaptation deep transfer learning method for cross-structure health monitoring using guided waves. *Structural Health Monitoring.* 21.

Hong, X., Zhang, B., Liu, Y., Qi, H., Li, W., 2020. Deep-learning-based guided wave detection for liquid-level state in porcelain bushing type terminal. *Structural Control and Health Monitoring*. 28.

Zhang, B., Yang, D., Hong, X., Jin, G., 2022. Deep emulational semi-supervised knowledge probability imaging method for plate structural health monitoring using guided waves. *Engineering with Computers.* 38.

Behravan, A., Tran, T., Li, Y., Davis, M., Shaikh, M., deJong, M., Hernandez, A., Brand, A., 2023. Field Inspection of High-Density Polyethylene (HDPE) Storage Tanks Using Infrared Thermography and Ultrasonic Methods. *Applied Sciences.* 13. 1396.

Behravan, A., deJong, M., Brand, A., 2021. Laboratory Study on Non-Destructive Evaluation of Polyethylene Liquid Storage Tanks by Thermographic and Ultrasonic Methods. *CivilEng.* 2. 823-851.

Gaisin, R.S., Tyukanko, V.Yu., Demyanenko, A.V., 2021. Developming a Method for Ultrasonic Quality Control of Plastic Products Obtained by Rotary Moulding Method. *Russian Journal of Nondestructive Testing*, p. 34–40.

Gaisin, R.S., Tyukanko, V.Yu., 2020. Review of Non-Destructive Testing Methods for Assessing the Quality of Plastic Products Manufactured by Rotational Molding. International Scientific and Practical Conference "Kozybayev Readings – 2020: Priority Directions of Development, Achievements, and Innovations in Modern Kazakhstani Science". pp. 254-256.

Gomes, F.P.C., Thompson, M.R., 2017. Analysis of Mullins Effect in Polyethylene Using Ultrasonic Guided Waves. Polym. Test. 2017, 60, 351–356. Published manuscript at Polymer Testing Licensed under the CC BY-NC-ND 4.0.

Gomes, F.P.C., Thompson, M.R., 2018. Nondestructive Evaluation of Sintering and Degradation for Rotational Molded Polyeth-ylene. Polym. Degrad. Stab. 2018, 157, 34–43. Published manuscript at Polymer Degradation and Stability Licensed under the CC BY-NC-ND 4.0.

Gomes, F.P.C., Garg, A., Mhaskar, P., Thompson, M.R., 2019. Data-driven smart manufacturing for batch polymer processing using a multivariate nondestructive monitoring. Ind. Eng. Chem. Res. 58.

Tyukanko, V, Demyanenko, A, Semenyuk, V, Dyuryagina, A, Alyoshin, D, Tarunin, R, Voropaeva, V., 2023. Development of an Ultrasonic Method for the Quality Control of Polyethylene Tanks Manufactured Using Rotational Molding Technology. Polymers (Basel).

Dyuryagina, A.N., Lutsenko, A.A., Tyukanko, V.Yu., 2019. Study of the disperse effect of polymeric surface–active substances in acrylic dispersions used for painting oil well armature. *Bull. Tomsk. Polytech. Univ. Geo Assets Eng*. 330 (8), 37–44.

Dyuryagina, A., Lutsenko, A., Ostrovnoy, K., Tyukanko, V., Demyanenko, A., Akanova, M., 2022. Exploration of the Adsorption Reduction of the Pigment Aggregates Strength under the Effect of Surfactants in Water–Dispersion Paints. *Polymers*, 14, 996.

Dyuryagina, A., Lutsenko, A., Demyanenko, A., Tyukanko, V., Ostrovnoy, K., Yanevich, A., 2022. Modeling the wetting of titanium dioxide and steel substrate in water–borne paint and varnish materials in the presence of surfactants. *Eastern–European Journal of Enterprise Technologies*, 1 (6 (115)), 31–42.

Tyukanko, V.Y., Duryagina, A.N., Ostrovnoy, K.A., Demyanenko, A.V., 2017. Study of wetting of aluminum and steel substrates with polyorganosiloxanes in the presence of nitrogen–containing surfactants. *Bull. Tomsk. Polytech. Univ. Geo Assets Eng*. 328, 75–81

Ostrovnoy, K., Dyuryagina , A. ., Demyanenko, A., & Tyukanko, V., 2021. Optimization of titanium dioxide wetting in alkyd paint and varnish materials in the presence of surfactants. *Eastern–European Journal of Enterprise Technologies*, 4(6(112), 41–50.

Tyukanko, V., Demyanenko, A., Dyuryagina, A., Ostrovnoy, K., Lezhneva, M., 2021. Optimization of the Composition of Silicone Enamel by the Taguchi Method Using Surfactants Obtained from Oil Refining Waste. *Polymers 2021*, 13, 3619.

Tyukanko, V., Demyanenko, A., Dyuryagina, A., Ostrovnoy, K., Aubakirova, G., 2022. Optimizing the Composition of Silicone Enamel to Ensure Maximum Aggregative Stability of Its Suspensions Using Surfactant Obtained from Oil Refining Waste. Polymers 2022, 14, 3819.

Zhanibekov, N., Brilkov, S., 2023. Mathematical modeling of the influence of technological parameters of rotary molding on the amplitude of the ultrasonic bottom signal. *V International Scientific Forum on Computer and Energy Sciences* (WFCES 2023).