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OPTIMIZATION OF SCANNING PARAMETERS OF COMPUTED RADIOGRAPHY FOR CHARACTERIZATION OF EXPANDED POLYSTYRENE

Summary

Because of the unique characteristics of imaging plates, computed radiography (cRT) enables the development of new radiographic techniques that were not possible with conventional film radiography, including material characterization. In this case, achieving maximum radiographic image quality is imperative which implies that every parameter of the cRT workflow must be controlled.

The paper presents an analysis of the scanning parameter influence on the characterization of the cell structure of expanded polystyrene (PS-E). For this purpose, an experiment was conducted varying three main scanning parameters: resolution (Res), laser power (LP) and photomultiplier tube gain (PMT). In order to determine the significance of each scanning parameter for the radiographic image quality, a parameter called „worthiness" was introduced. Also, using a mathematical model developed on the basis of the experiment, a methodology for the selection of scanning parameters for the cRT of PS-E of different compressive strength is proposed.

Key words: *computed radiography technique, expanded polystyrene, optimizing scanning parameters*

1. Introduction

Mechanical and thermal properties of expanded polystyrene (PS-E) are correlated with its structural density. The quality control of these properties is necessary to monitor and optimize the process of expanded polystyrene production. Therefore, possibilities of the non-destructive characterization of PS-E are studied by determining measurable features of its structure, aiming at estimating the utilization properties of PS-E. For this purpose, the radiographic non-destructive method is considered. It is assumed that information about the structural density and structure variation of the inspected volume of PS-E can be obtained by the analysis of selected measurable features of radiographic images.

Industrial computed radiography (cRT) is a process with three steps: (I) radiographing the test component, (II) scanning the exposed image plate and (III) digital image evaluation and analysis.

The scope of the radiographing the test component is the latent image generation in the structure of the used sensor. The content of the latent image is a result of the spatial exposure of the sensor to X or gamma ray radiation that passed through the structure of the test component.

With conventional film radiography, the latent image is created by the transformation of silver halide crystals that afterwards have to be developed chemically. In the case of cRT, the latent image is created in a radiation sensitive active layer of imaging plates, called photostimulable phosphor. Subsequent to the X or gamma ray radiation, electrons in the active layer are excited and trapped in a semi-stable, higher energy state ([1], [2]).

By scanning the image plate the latent image is, by means of laser stimulation on a point-by-point basis, initially converted into an analogue light response that is then converted into a digital signal. The trapped electrons are released by the laser beam energy stimulation and a process called photostimulated luminescence (PSL) occurs. It results in the emission of blue light wavelengths with an intensity proportional to the original radiation exposure. The photomultiplier tube (PMT) amplifies and converts blue PSL light into a digital signal representing a pixel of digital image. The remaining latent image information in the active layer of imaging plates has to be erased by using special high-intensity lamps and light wavelengths, after which the imaging plate is ready for next exposure.

When considering a possible application of cRT for the purpose of the characterization of PS-E, the key prerequisite is achieving high quality of the digital image. With this objective in mind, the influence and optimization of the scanning parameters are studied and presented in this paper.

2. Expanded polystyrene structure

Expanded polystyrene (PS-E) that is used as a thermal insulation product in civil engineering industry is manufactured by the process of steam moulding. PS-E is manufactured in the form of slabs as closed cell, lightweight, rigid plastic foam. Properties are declared according to the standard HRN EN 13164 [3], where it is referred to as EPS (nomenclature accepted in civil engineering industry). It is made of a polymeric matrix and gas phase. In 1 m^3 of PS-E there is up to $6 \cdot 10^9$ closed cells with diameters from 50 μm to 500 μm. Gas phase can take up to 98 % of its volume, and the rest is a 1.5 μm to 5 μm thick PS membrane. The main feature that characterizes this cellular material is its density and production process ([4], [5]). The density is determined by the size of expanded polystyrene beads [6].

Test samples with dimensions of 200 mm x 200 mm were cut from PS-E boards 1000 mm x 500 mm in size and prepared for the experimental work. Thickness of all test samples was 80 mm. Declared values of compressive strength for PS-E boards were 50 kPa, 100 kPa, 150 kPa and 200 kPa.

Fig. 1 shows the macrostructure of expanded polystyrene for different declared values of compressive strength. As it can be seen, the higher is the density and, accordingly, the higher value of compressive strength, the smaller is the diameter of PS-E beads. Also, as density increases, it can be noticed that the difference between the diameters of the beads becomes greater.
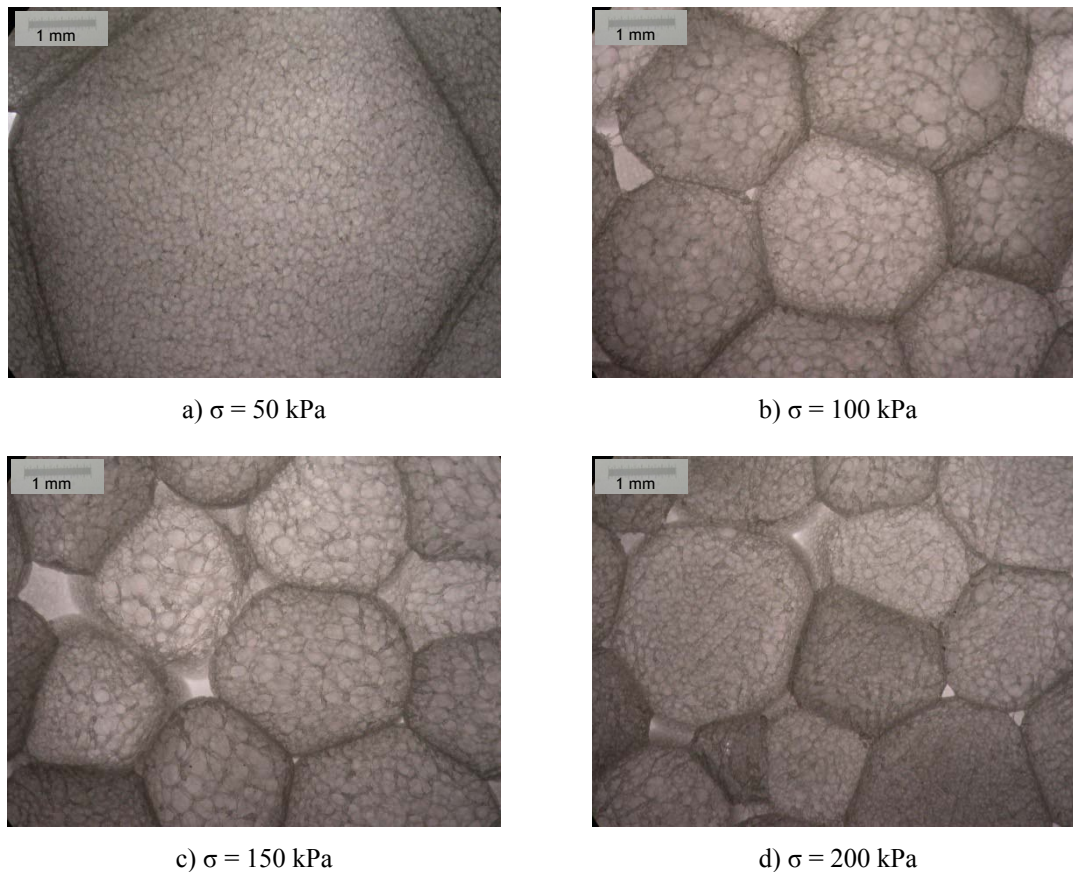
a) σ = 50 kPa

b) σ = 100 kPa

c) σ = 150 kPa

d) σ = 200 kPa

Fig. 1 Macrostructure of PS-E of different compressive strength values:
a) 50 kPa, b) 100 kPa, c) 150 kPa, d) 200 kPa

3. Experimental setup

The X-ray tube ISOVOLT 160 M2 0.4/1.5, manufactured by GE Inspection Technologies, was used for the exposure of PS-E samples. Polystyrene foam requires low energy. It is due to low density (15 kg/m^3 to 40 kg/m^3) and a small mass attenuation coefficient (2.6 cm/g^2 at 10 kV) [7]. Further, the used X-ray tube was the only available tube that makes it possible to select the focus of 1 mm, which ensures a better outcome of the spatial resolution of the radiographic image.

The scanner VMI 5100MS was used as a read out device that extracts the latent image from the active layer of the imaging plate and converts it into a digital image. The majority of available scanners for the industrial cRT allow adjustment of three scanning parameters independently: scanning resolution, photomultiplier tube gain and laser power.

Scanning resolution represents the pixel size on the digital radiographic image and is determined by the laser beam size and sampling pitch of the scanner, which is regulated by scanning speed. Laser power represents the energy of the laser beam. Photomultiplier tube gain represents the amplification of the light signal after its transformation in the electrical signal. The amount of amplification is regulated by voltage on the photomultiplier tube.

All scanning parameters interfere with each other and each parameter contributes to the final pixel size and intensity as well as to the amount of digital noise on the hrmage. For that reason it is important to optimize the parameters in order to achieve the best possible image quality.

KODAK INDUSTREX Flex GP (General Purpose) Digital Imaging Plate was used. Lead screens were not used.

Optimal scanning parameters will be obtained by analyzing the achieved digital image quality for different sets of scanning parameters while exposure parameters will be fixed.

4. Proposed methodology for image analysis

VMI 5100MS scanner has a 16 bit analog-digital converter resulting in the 16-bit depth of digital raster images. The 16-bit grayscale TIFF image format was exported without any form of compression for the purpose of image analysis.

To obtain useful features from digital images a proper algorithm should be applied. A histogram of pixel intensity values was analysed for the purpose of the cell structure characterization.

The arithmetic mean of pixel intensities over the region of interest (ROI) is the first moment about origin and the first analysed feature extracted from the digital image.

Graphically, it can be presented on a histogram of the ROI where it is distinguished as a measure of location. The size of the ROI is 10 mm x 10 mm and it was constant for all analyses of digital radiographic images.

In order to determine the optimal scanning parameter, the parameter name *worthiness* is proposed and denominated as δ. For every state of experiment worthiness is determined by the following equation:

$$\delta = \left| \frac{\overline{I_u} - \overline{I_{ref}}}{s_{I_u} + s_{I_{ref}}} \right| \tag{1}$$

where the arithmetic mean of intensity $\overline{I_u}$ is measured in the ROI in the sample digital image, $\overline{I_{ref}}$ is the arithmetic mean of the intensity measured in the ROI in the reference sample digital image, $\overline{s_{I_u}}$ is the standard deviation of intensity measured in the ROI in the sample digital image and $\overline{s_{I_{ref}}}$ is the standard deviation of intensity measured in the ROI in the reference sample digital image.

Optimal scanning parameters are going to be determined by the maximum value of worthiness:

$$\text{optimal scanning parameters} = \max(\delta)_i \tag{2}$$

where i represents the state of experiment with the maximum value of worthiness, δ. Also, $i = 1$ to n where the finite number of the state of experiment, n, is given by the experiment design.

5. Experiment design

The model of dependence of intensity and worthiness upon variable scanning parameters and compressive strength can be expressed by the regression equation of higher order. The order of experiment is random and is generated by the software Design-Expert 8.0.7.1 (available trial version). A full factorial design of experiments 3^4 is used to analyse the influence of four variable factors on the value of intensity and worthiness. The four variable factors are PMT - gain of photomultiplier tube (V), Res - resolution (μm), LP - laser beam power (J/m^2) and σ - compressive strength of PS-E (kPa).

In order to determine the optimal radiographic exposure a preliminary experiment was carried out. Exposure was chosen so that the pixel intensity values for the reference sample were in the middle of the intensity range (app. 32000). This radiographic exposure in combination with the great exposure latitude of imaging plates ensured that no over or under exposure will occur in digital radiographic images of test samples of different compressive strengths [8].

The preliminary experiment showed that optimal exposure parameters are: X-ray tube voltage of 15 kV, exposition of 420 mAs (t = 120 s) and 1 m film focus distance. These exposure parameters were held constant during the experiment.

Fig. 2 shows test samples of different compressive strengths set on the imaging plate and ready for the exposure, and Fig. 3 shows a digital radiographic image of test samples for the following exposure and scanning parameters: X-ray tube voltage of 15 kV, exposition of 420 mAs (t = 120 s), gain of photomultiplier tube of 4.25 V, laser beam power of 10 J/m^2 and resolution of 50 μm. In Fig. 3, test sample 1 exhibits the compressive strength of 200 kPa, test sample 2 the strength of 150 kPa and test sample 4 exhibits the compressive strength of 50 kPa. Sample 3 with the compressive strength σ = 100 kPa is used as a reference sample for the calculation of worthiness (Fig. 3).
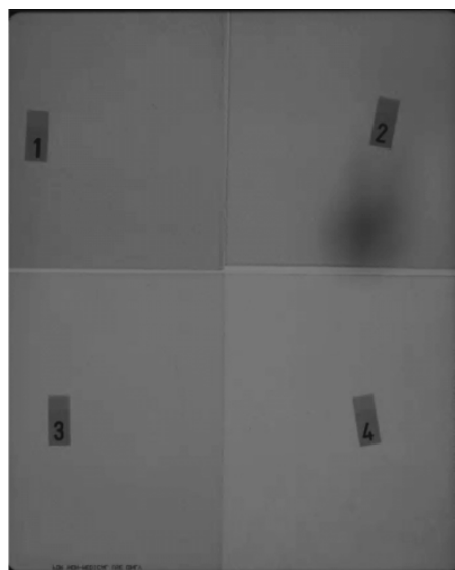

Fig. 2 Test samples on imaging plate.

Fig. 3 cRT digital radiographic image of test samples.

6.   Mathematical model

The values of worthiness introduced into the model represent the arithmetic mean of the calculated values of worthiness according to equation 1 for three different regions of interest in the digital radiographic image. The analysis of variance (ANOVA) has shown that the dependence of worthiness upon input scanning parameters can be best expressed by a reduced mathematical model without transformation (lambda = 1.0).

Table 1 gives an analysis of variance for the reduced model for the determination of the worthiness value, where C is resolution in μm and D is the value of compressive strength of PS-E in kPa.

The Model F-value of 45.5 implies the model is significant. There is only a 0.01 % chance that the „Model F-Value" so high could occur due to noise. Thereby the model is significant. Values of „Prob > F" less than 0.05 indicate that the model terms are significant. In this case, C and D as first order linear terms and C^2 and D^2 as second order linear terms are significant. Model terms A: PMT - gain of photomultiplier tube in V and LP: laser beam power in J/m^2 are not significant. Also, there is no interaction between the model terms.

Table 1 Analysis of variance for reduced model for determination of worthiness value.

Source	Sum of Squares	df	Mean Square	F Value	p-value Prob>F	significant
Model	98.45	4	24.61	45.50	< 0.0001	significant
Model terms:						
C	13.02	1	13.02	24,08	< 0.0001	significant
D	26.61	1	26.61	49.20	< 0.0001	significant
C^2	4.19	1	4.19	7.75	0.00068	significant
D^2	67.77	1	67.77	125.27	< 0.0001	significant
Residual	41.12	76	0.54			
Cor Total	139.57	80				

Final equation in terms of coded factors:

$$\delta = 1.31 - 0.49 \cdot C + 0.70 \cdot D + 0.48 \cdot C^2 + 2.22 \cdot D^2 \tag{3}$$

The mathematical model with the coded factors from equation 3 is translated to the mathematical model in terms of actual factors from equation 4. Final equation in terms of actual factors that will represent dependence of worthiness upon resolution as a scanning parameter and compressive strength as a feature of expanded polystyrene is as follows:

$$\delta = 9.22954 - 70.048439 \cdot \text{Res} - 0.089438 \cdot \text{PS-E} + 1.9308410 \cdot 10^{-4} \cdot \text{Res}^2 \\ + 3.95195 \cdot 10^{-4} \cdot \text{PS-E}^2 \tag{4}$$

where Res is resolution in μm and PS-E is the value of compressive strength of PS-E in kPa.

Fig. 4 shows a contour view of the mathematical model of the dependence of worthiness on the resolution and the value of compressive strength measured in the digital radiographic image.
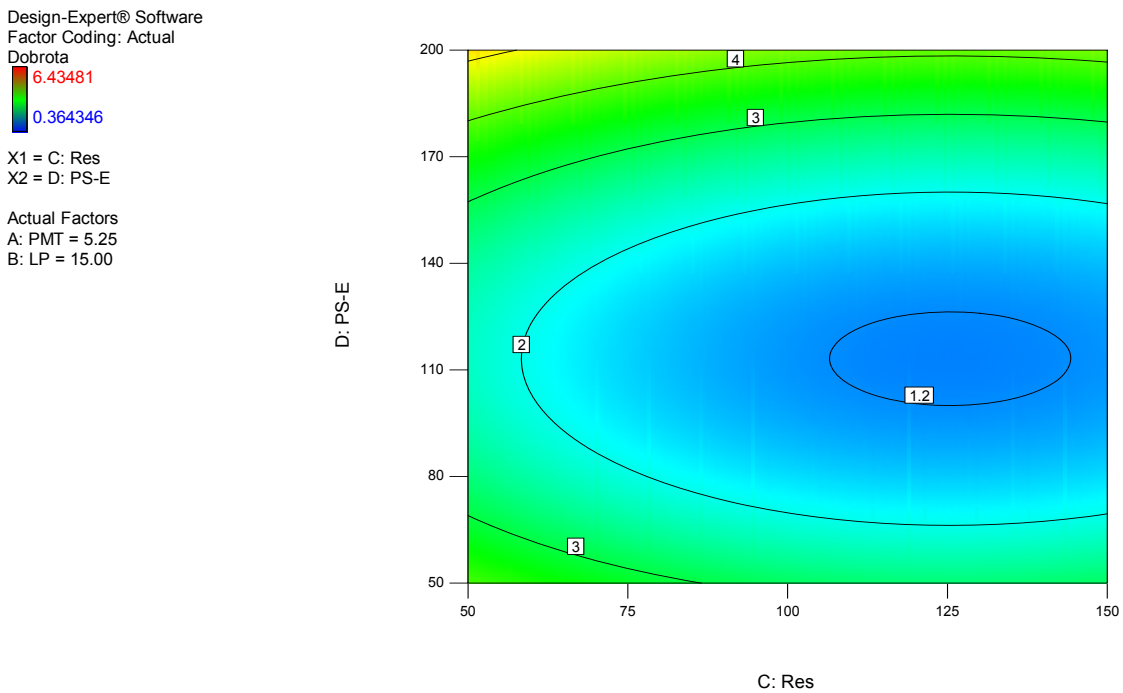
Fig. 4 Contour view of the mathematical model of dependence of worthiness on C:Res and D:PS-E measured in digital radiographic image (actual factors are A:PMT = 5.25 i B:LP = 15 J/m^2).

The following figures show the dependence of maximum worthiness on the value of compressive strength (Fig. 5) and dependence on the value of resolution (Fig. 6). As it can be seen the value of worthiness is lower as compressive strength increases. This dependence is valid until the value of compressive strength reaches approximately 116 kPa when the value of worthiness increases with a further increase in compressive strength.
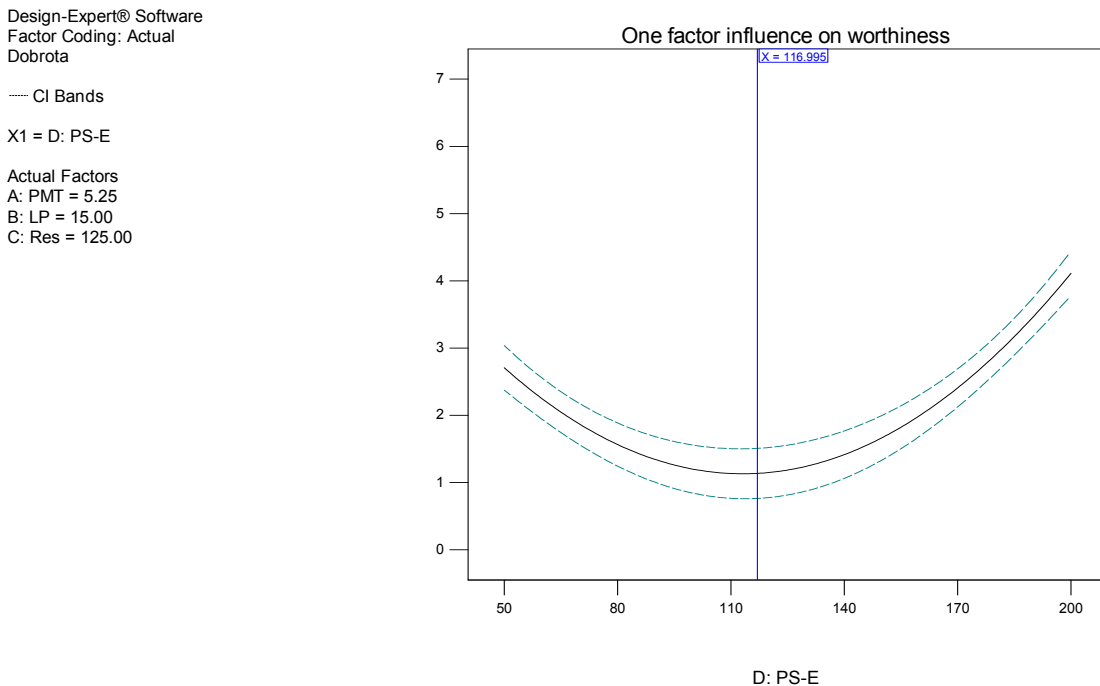

Fig. 5 Dependence of maximum worthiness on value of compressive strength (actual factors are A:PMT= 5.25 V, B:LP = 15 J/m^2 and C:Res = 125 μm).
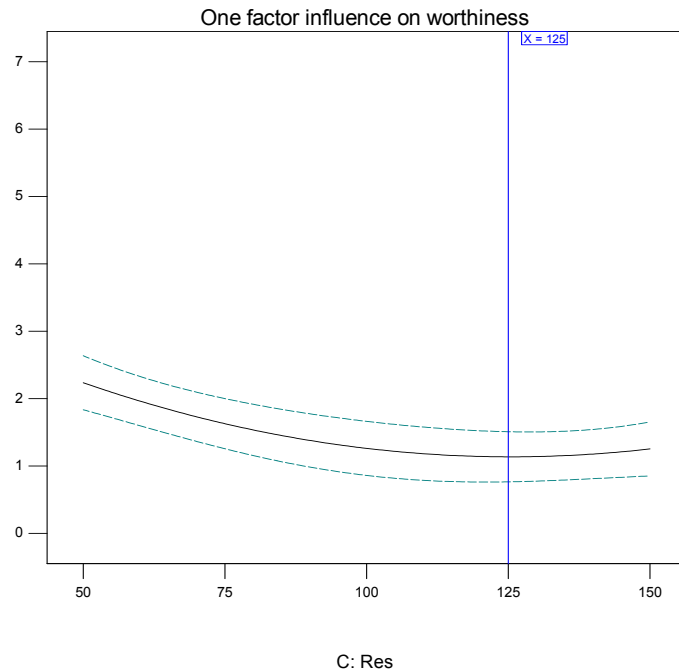
Fig. 6 Dependence of maximum worthiness on value of resolution
(actual factors are A:PMT= 5.25, B:LP = 15 J/m^2 and D:PS-E = 117 kPa).

7. Parameter optimization

Optimal scanning parameters are determined by using the method of parameter optimization (graphical and numeric) and the software Design-Expert 8.0.7.1. The optimization was done within the range of the following setting parameters:

- Range of the gain of photomultiplier tube: from 4.25 V to 6.25 V
- Laser power range: from 10 J/m^2 to 20 J/m^2
- Resolution: from 50 μm to 150 μm
- Compressive strength: in the range by 10 kPa, i.e., from 180 kPa to 190 kPa
- Target pixel intensity: in the range from 30000 to 35000
- Worthiness: the goal is to have the maximum value of worthiness inside the set range for compressive strength and pixel intensity.

The method of parameter optimization is shown for expanded polystyrene with the value of compressive strength set in the range from 180 kPa to 190 kPa. Table 2 gives constrains that are set for the parameter optimization for the given example.

Table 2 Set constrains for optimization of scanning parameters for expanded polystyrene with value of compressive strength in range from 180 kPa to 190 kPa.

CONSTRAINS	Goal	Minimum value	Maximum value
Model term:			
A:PMT	range	4.25	6.25
B:LP	range	10	20
C:Res	range	50	150
D:PS-E	range	180	190
I_{sred}	range	30000	35000

The goal is to obtain a maximum value of worthiness within the set ranges. The proposed optimal scanning parameters that are results of the parameter optimization are given in Table 3. There are nine groups of optimal scanning parameters in total, for which the value of worthiness is 4.56354 and the value of desirability is 0.692 (maximum value of desirability is 1). These values of worthiness and desirability are maximum values that can be achieved for the set constrains.

Table 3 Proposed optimal scanning parameters for expanded polystyrene with value of compressive strength in range from 180 kPa to 190 kPa.

RESULT	PMT	LP	Res	PS-E	I_{sred}	Worthiness	Desirability
1.	5.56	19.63	50	190	32549.5		
2.	5.65	15.99	50	190	31808.9		
3.	6.21	10.72	50	190	31900.6		
4.	5.45	18.14	50	190	31036.7		
5.	5.44	17.16	50	190	30330.2	4.56354	0.692
6.	5.89	15.70	50	190	34019,8		
7.	5.35	19.79	50	190	30324.9		
8.	5.74	14.39	50	190	31510.5		
9.	5.52	15.32	50	190	30073.5		

Fig. 7 and Fig. 8 show areas with the maximum value of worthiness and desirability for the given example after the parameter optimization. Fig. 7 represents an area of maximum desirability for the scanning resolution of 50 μm and Fig. 8 for 100 μm. Maximum values of worthiness and desirability are given in dependence on the scanning parameters, laser power and photomultiplier tube voltage, and with respect to the set constrains.

Also, as it can be seen, the maximum value of desirability in the set range of PS-E is achieved with the scanning resolution value of 50 μm.
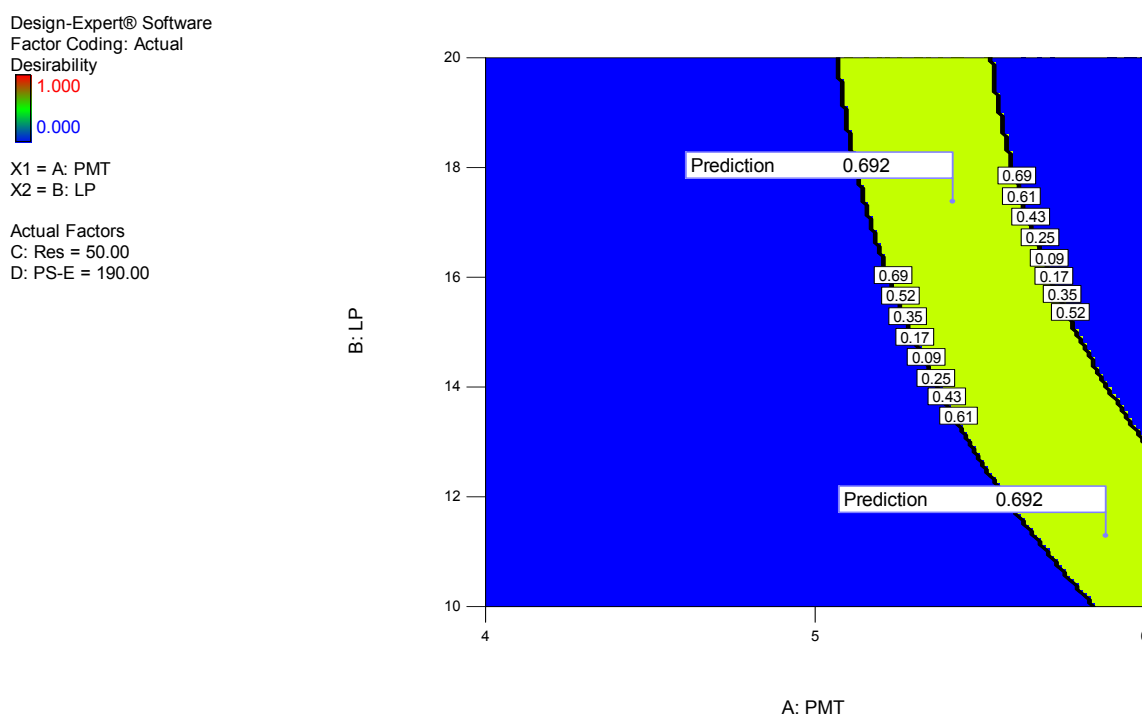

Fig. 7 Dependence of desirability on A:PMT and B:LP with respect to set constrains
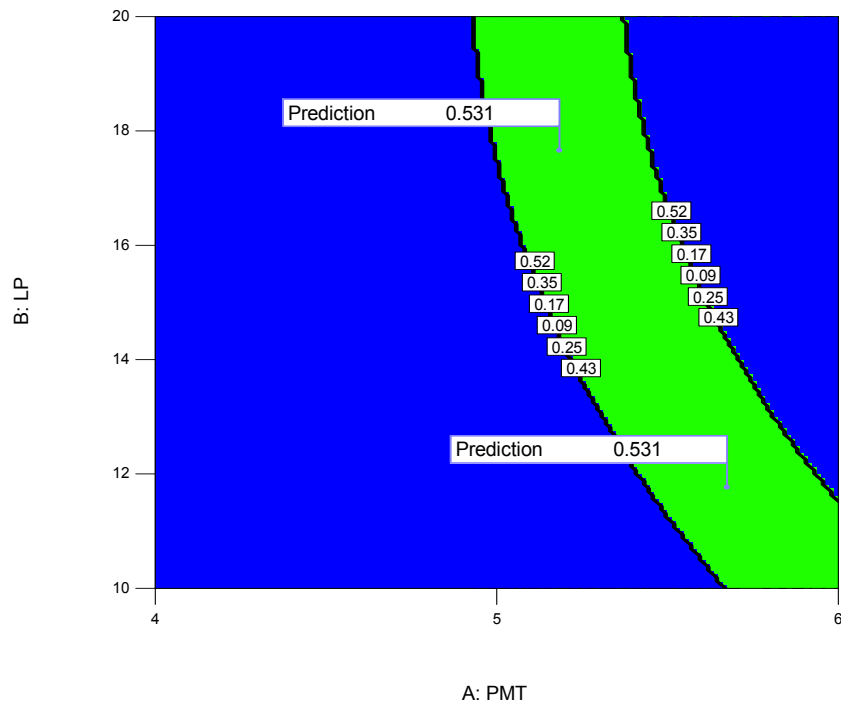where actual factors are C:Res=50 μm and D:PS-E=190 kPa.

Fig. 8 Dependence of desirability on A:PMT and B:LP with respect to set constrains
where actual factors are C:Res=100 μm and D:PS-E=190 kPa.

By analogy with the given example, optimal scanning parameters are determined for all ranges of compressive strength.

8. Analysis of results

According to final equation 4 in terms of actual factors there are two first order linear factors that influence worthiness of the digital radiographic image. They are (listed from maximum to minimum influence on the model): C – scanning resolution [μm] and D – compressive strength [kPa].

Only one of these two significant factors, that is scanning resolution, can be optimized while compressive strength is an attribute for the sample material. Although laser power and photomultiplier gain do not significantly influence the value of worthiness according to the proposed model, they do influence the pixel intensity and must be optimized according to the radiographic exposure for the target pixel intensity values.

From the proposed mathematical model and according to Fig. 4 to Fig. 8, the following can be concluded:

1. Influence of factor C – resolution on the value of worthiness can be described by a quadratic curve. The value of worthiness is lower as compressive strength increases. This dependence is valid until the value of compressive strength reaches approximately 116 kPa when the value of worthiness increases with a further increase in compressive strength.

2. Factor D compressive strength has linear influence on the model. For all values of compressive strength that were observed in the model, the value of worthiness increases with the smaller pixel size (lower values of factor C). At values of

resolution greater than 125 μm, worthiness increases, but with a significantly less sloping curve.

3. There are second order linear terms C^2 and D^2.

4. There are no interactions between C and D.

9. Conclusion

Optimization of scanning parameters is often neglected in the cRT workflow. In general, there are no uniform procedures or known methodology for the determination of optimal scanning parameters for the cRT technique.

In order to enable the characterization of cell structure by means of cRT, all parameters in the cRT workflow must be controlled. The paper shows that scanning parameters have an influence on the quality of digital radiographic images. For that purpose, an experiment with expanded polystyrene samples was carried out and a model for scanning parameter optimization for different expanded polystyrene compressive strengths is proposed as well as a worthiness parameter. According to the model, only scanning resolution significantly influences the proposed worthiness value.

Due to a potential application of computed radiography (cRT) for the characterization of PS-E structures, and indirectly for the estimation of the production quality of PS-E, the quantification of relevant reliability parameters is imperative. In qualitative terms, this involves defining a characteristic response of each constituent of the characterization series.

Further research will be focus on the determination of the extent and the way the parameters of the process of continuous transformation of the response signal affect the reliability of test results.

Acknowledgement

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