13 Neural networks aided future events scenarios presented on the example of laser surface treatment

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Abstract

Purpose: *The purpose of the chapter is to present a methodological concept allowing to demonstrate the development directions of materials surface engineering according to the level of generality and the intensity of the phenomena analysed on other phenomena.*

Design/methodology/approach: *A set of analytical methods and tools was used to present the development directions of materials surface engineering at the three levels analysed, i.e.: a macro-, meso- and microlevel. The analytical methods and tools comprise the scenario method, artificial neural networks, Monte Carlo method, e-Dephix method, statistical lists as bar charts, foresight matrices together with technology development tracks, technology roadmaps, technology information sheets and the classical materials science methods.*

Findings: *A research methodology allowing to combine a presentation and description of the forecast future events having a varied level of generality and capturing the cause and effect relationships existing between the events.*

Research limitations/implications: *The methodological concept discussed, implemented with reference to materials surface engineering, has a much broader meaning, and can be successfully applied in other technology foresights, and also in industrial and thematic foresights after minor modifications.*

Practical implications: *The outcomes of the research conducted may be and should be used in the process of creating and managing the future of materials surface engineering and, within the time horizon of 20 years, may and should influence positively the development of the economy based on knowledge and innovation, sustainable development and the statistical level of the technologies used in industry, especially in small- and medium-sized enterprises.*

Originality/value: *An own methodological concept constitutes an original way of presenting the development directions of the investigated field of knowledge. The use of neural networks represents an innovative and experimental approach unseen in foresight methodology to date.*

Keywords: *Scenario method; Neural networks; Foresight; Laser surface treatment*

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1. Introduction

The contemporary techniques of building scenarios were used for the first time in the 50's of the last century and their widespread use in the public and business area has started since the seventies [1]. According to the foresight technology, the scenarios reflect the future opportunities and are developed in a systematised way and their task is to capture the holistic sense of particular conditions [2]. The building of scenarios consists of describing the events in the area investigated and indicating their logical and chronological sequence including the macroeconomic factors influencing positively or negatively the forecast development of the events, thus brings specific opportunities and risks. The extensive research [3] who has analysed altogether 860 foresight projects, pursued globally, indicates that the creation of scenarios of future events is the third most often used method. The method was applied in 43% of the projects analysed with only a literature review (55%) and expert panels (51%) being ranked higher. This result translates directly into the applicability of the scenario method in the particular regions of the World. The applicability of the scenario method in Northwest Europe, Eastern Europe, North America and Asia ranges between 40 to 50%. The method has been used less often in Northern Europe (approx. 30% of projects) and North America (approx. 20% of projects) [4]. Evaluative investigations held for 40 foresight projects that had already been implemented or have been implemented in Poland [5] point out that the scenario method enjoys greater popularity in Poland as compared to the global average. The method has been used in almost the three-third of the projects and ranked first among all the methods applied, staying ahead of the Delphi method and the expert panels method that ranked just behind. The building of scenarios of future events is also found among the tasks planned for implementation as part of technology foresight concerning the priority innovative technologies and directions of strategic development of material surface engineering [6]. This chapter presents methodology assumptions for the research works conducted as well as the application examples of the scenario method at the different levels of generality of the issues discussed.

2. The scenario creation custom idea

The references [7-11] indicate that there is no one correct and generally accepted method of creating the scenarios of future events or a management algorithm recommended for implementation in the scenario creation process. In fact, the algorithm is created each time from the scratch by the practicians implementing a specific project [1]. The same refers to building the scenarios presenting the forecast future of materials surface engineering where a methodological challenge exists of combining skilfully the presentation and description of the phenomena characterised by varied generality and to capture the cause and effects relationships existing between them. In order to solve the so formulated research task, all the analysed phenomena are divided into the three groups:

- A **macrogroup** with all the single critical phenomena of general nature characterised by strong interaction with the other phenomena;
- A **mesogroup** with a limited number of phenomena interacting moderately with the other phenomena;
- A **microgroup** comprising numerous specific phenomena highly sensitive to the interaction of other phenomena.

The classification adopted is presented graphically in Fig. 1. The approach shown allows for a two-fold method of deductive reasoning, i.e. analysis or synthesis. The analytical approach consists of determining what macroscenario will occur in the future for the specific combination of the current micro- and mesofactors. Deductive reasoning by way of a synthesis, adopted for the undertaken research concerning the forecast development of materials surface engineering, forces us to seek such a combination of micro- and mesofactors that would contribute, with

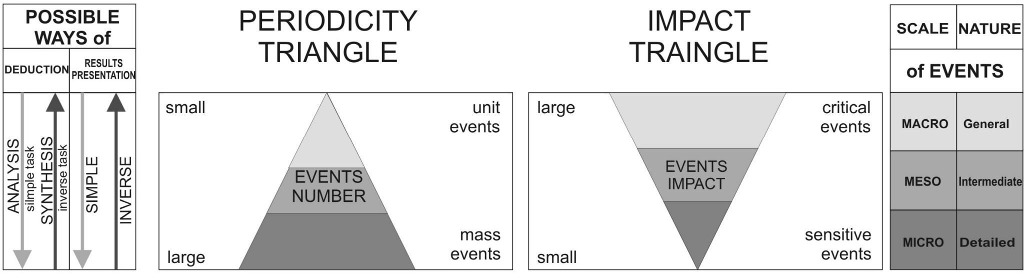


Figure 1. *Overview of the phenomena subjected to investigations with the scenario method*

a specific probability, to the occurrence of each of the three possible macroscenarios in the future. The presentation of research outcomes that is unrelated to the method of deductive reasoning is another issue. This chapter uses a simple method of presenting the research results and the phenomena investigated are presented in the individual sub-chapters starting with the highest level of generality (macro), through an indirect level (meso) ending with the most detailed notions (micro). According to the periodicity triangle shown in Fig. 2 created for the materials surface engineering research conducted, the number of the phenomena considered increases along with the growing level of specificity. 3 scenarios of future events are considered at the macrolevel: optimistic, neutral and pessimistic with their overview presented in Table 1. The mesolevel is grouping 16 key factors influencing the development of materials surface engineering and 14 thematic areas analysed under the foresight research. The micro-level is represented by 140 groups of critical technologies. Specific technologies with an unknown *n* number can be distinguished between for them, often differing in details only. They can, however, substantially condition the development prospects of a particular technology and its applicability in the industrial practise. Considering the scale of the phenomena described, the full results of the research cannot be included in one chapter only. A representative group of laser technologies in surface engineering was, therefore, chosen (mesoscale) with special focus on laser remelting and alloying, especially with reference to hot-work alloy tool steels (microscale) and the scenario creation concept developed is presented by using such example. The concept is much more far-reaching and has been applied with reference to all the thematic areas, groups of critical technologies and specific technologies analysed for the research work conducted i.e. [12-20]. The analytical methods and tools for creating the scenarios of future events for materials surface engineering are entered into the periodicity triangle (Fig. 2).

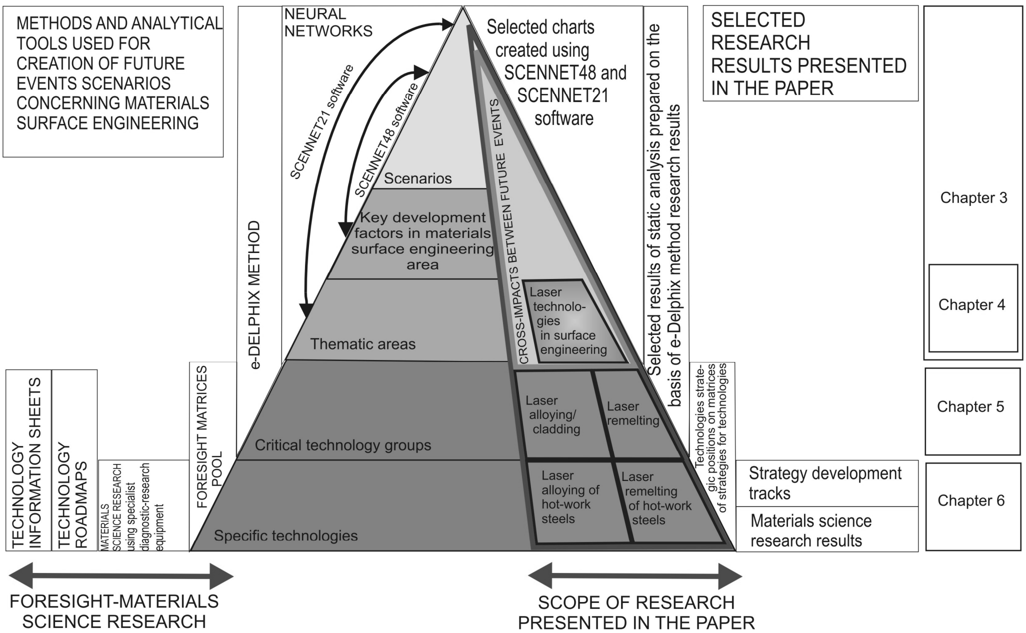


Figure 2. *Analytical methods and tools for creating the scenarios of future events for materials surface engineering and the selected research results presented in the chapter*

Table 1. *Overview of three alternative macroscenarios of events development*

Forecast Macroscenarios	Overview of forecast macroscenario type
Optimistic: Race won	The global economic crisis has been prevented and economic growth is experienced based on peaceful co-operation and international integration. The competitive position of the European Union is growing among the world economies. Numerous reforms are being successfully implemented in Poland having social approval the purpose of which is the actual transformation of economy supporting the sustainable development of the knowledge-based economy. Poland is skilfully combining endogenic growth factors with foreign investments and the effective use of EU funds. The consequence of widespread actions planned is the gradual improvement of the society's education, the wide-scale application of innovative and environmental friendly technologies in many thriving small and medium-sized companies (SMEs) and large corporations operating more and more often in high-tech industries, effective use of Poland's agricultural resources, and also the development of modern transport and ICT infrastructure. The economic, system, technological, financial and social potential available is used adequately to put into life the strategic development goal, statistically people are better off, social attitudes are optimistic and prospects for the coming years bright.
Neutral: Progress achieved	The world economic crisis has been prevented and the World is slowly returning to the growth path in the paradigm of sustainable growth based on co-operation and international integration, although the fear of terrorism and local wars still exists which, in unfavourable circumstances, may spread to many countries. The

Forecast Macroscenarios	Overview of forecast macroscenario type
	European Union needs to fight hard for its position among global economies, especially with regard to China and India emerging as world powers. There are efforts made in Poland, with different outcomes, to tackle reforms aimed at economy transformation and the reforms are often opposed by the society and people's reluctance towards change. Poland is trying to use the EU funds, but not all the money is managed effectively. The introduction of a knowledge-based economy and sustainable development brings results such as the growing education level of the society and its environmental awareness. The SME sector is developing at a constant but slow rate, and the level of implementing the innovative and environmental technologies leaves still much to wish for. Large corporations operate mainly in medium and low and medium and high technologies. The country is constantly facing problems in public finance, agriculture and healthcare, and the modern transport and ICT infrastructure is developing steadily but relatively slowly. The economic, system, technological, financial and social potential is only partly used to achieve strategic development goals, statistically people are slightly better off but social attitudes are mixed. Theoretically good development prospects for the coming years depend on the circumstances in the European and world economy, wise management of public funds in long term and on how quickly the relevant reforms are introduced supported with the society's involvement.
Pessimistic: Inclined plane	The global economic crisis has been slowed down to some degree only. The world is facing terrorism, growing oil prices, consequences of disasters and local wars spreading to more and more countries. The European Union stays behind other global economies, especially China and India emerging as global powers. Usually unsuccessful attempts are made in Poland to tackle reforms serving to transform economy that face social disapproval and strong reluctance towards changes. The EU funds allocated to Poland are smaller and smaller every year, and most of the money is used to save the current economy, whereas the level of investments is slowing down. The implementation of the knowledge-based economy and sustainable development concepts, initially boding well, is now weakening. The MSE sector is developing sluggishly, and innovative environmental technologies cannot be usually applied due to the lack of investments and the low availability of credits. Large corporations operate in medium and low and medium and high technologies, and many of them go bankrupt and move their head offices to Asia. The country is constantly facing problems in public finance, agriculture, healthcare, education and transport infrastructure. The economic, system, technological, financial and social potential is weakly utilised for fulfilling strategic development goals with the goals being, apparently, wrongly formulated. Statistically people are worse off which is accompanied by social unrests. Development prospects for the coming years are weak and Poland will be heading for a disaster if a sudden breakthrough is not experienced.

In addition, the results of the research chosen for presentation in the individual sub-chapters of the chapter are presented graphically. Sub-chapter 3 provides an overview of the methodological assumptions and the examples of the practical implementation of neural networks used for analysing cross impacts in order to identify how the key mesofactors of materials surface engineering development and the specific thematic areas condition the occurrence of each of the three alternative macroscenarios. Sub-chapter 4 includes a development forecast of laser technologies in materials surface engineering established based on the results of the e-Delphix method differing from the classical Delphi method in that experts are surveyed using in an electronic way and in that the level of generality for the questions asked to the experts is growing along with the subsequent iterations of the research. Sub-chapter 5 of this chapter discusses the strategic position of the relevant groups of critical laser surface treatment technologies against the thematic area of "Laser technologies in surface engineering" together with a statistical list presenting, in percents and as forecast by the experts, the values of growth, stabilisation and decrease in the importance of the individual critical technologies. At last, sub-chapter 6 contains the results of the materials science-foresight research concerning laser remelting and cladding of hot-work alloy tool steels with special emphasis laid on the results of materials science investigations and the strategic position of the specific analysed technologies presented in a matrix of strategies for technologies together with the forecast strategic development tracks. The scenarios of future events established concerning materials surface engineering can be characterised, according to the references [9, 21, 22], in a number of ways according to the various criteria of classification Fig. 3 shows an overview of the scenarios prepared for the research followed against the overview of optional scenarios according to the classification criteria adopted in an arbitrary manner.

3. Cross-impacts analysis made using neural networks

3.1. Methodological assumptions

Neural networks were used in a novel and experimental manner to cross impacts analysis. The analysis serves to identify how the key mesofactors of surface engineering development (e.g. collaboration between science and industry, number of specialised laboratories and R&D institutions, continuous improvement and high quality of technology, transparent and friendly legislation, international co-operation and EU funds) and the relevant thematic areas analysed (e.g. laser technologies, thermochemical technologies, nanotechnologies) may influence the occurrence of each of the macroscenarios. A data set elaborated according to the results of survey investigations was divided randomly into the three sub-groups: learning, validation

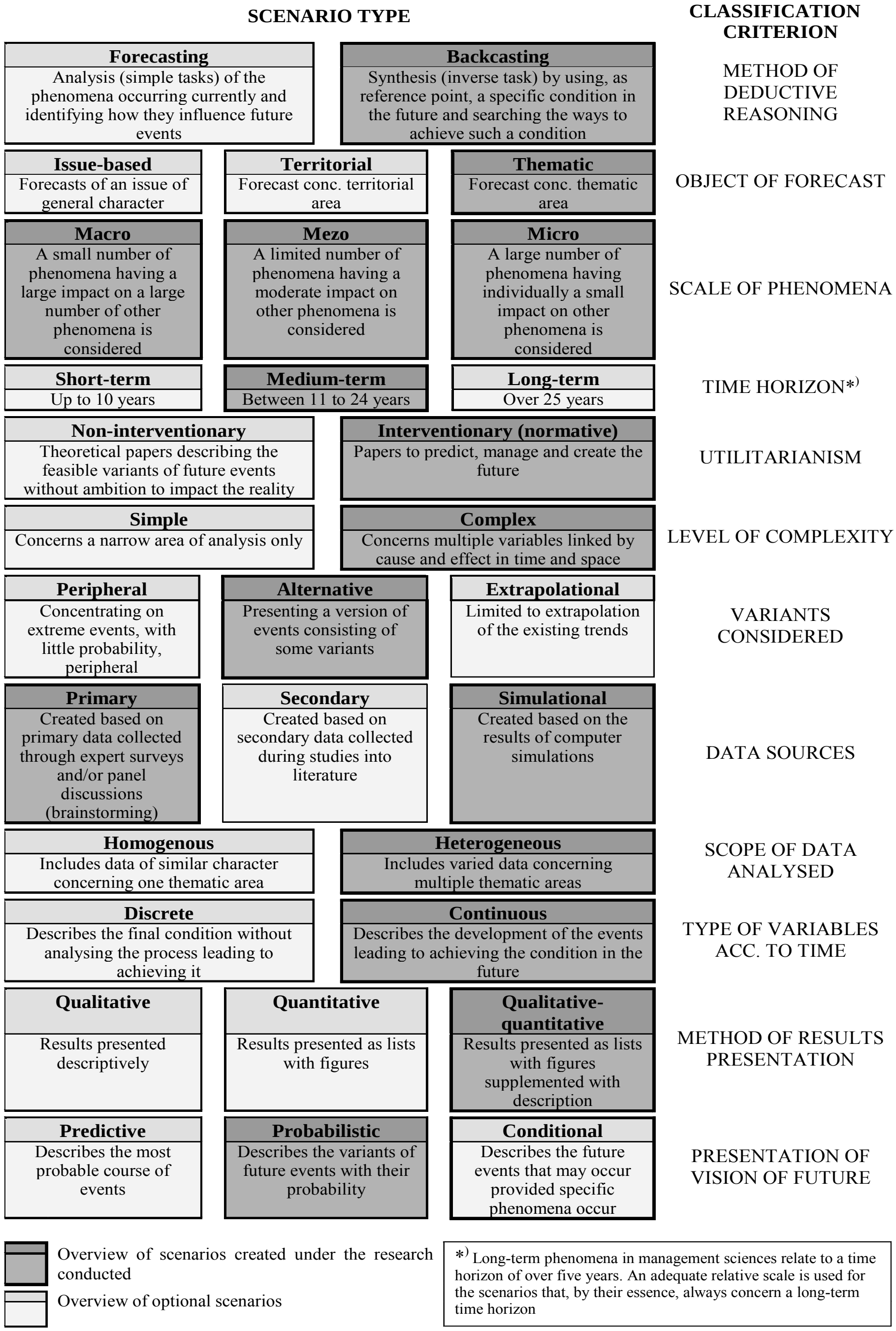


Figure 3. *Overview of the scenarios created under the research conducted against the overview of optional scenarios*

and testing sub-group. The data from the learning set was used for modifying network importance in the learning process and the data from the validation set was used for network evaluation in the learning process. The remaining part of the data, as a test set, was used to determine, independently, network efficiency after completing fully the network development procedure. The following values were used as the basic indicators of model quality evaluation: an average absolute error of network forecast, a standard deviation of the network forecast error, R Pearson's correlation coefficient for the value set and for the value obtained at the neural network output. The quality evaluation indicators of artificial neural networks were calculated for each of the separated sets. The similar values of the average error, standard error deviation and correlation coefficient confirm the generalisation ability of the network, i.e. an ability to generalise the knowledge acquired in the learning process.

9 models were created altogether using artificial neural networks by adopting, as dependent (input) variables, the probabilities of the occurrence of a growth trend, stabilised trend and/or declining trend determined for the key mesofactors conditioning the development of materials surface engineering and for the individual thematic areas for the research domain of M (Manufacturing) and P (Product). The first research field (M) reflects a manufacturer's point of view and encompasses the production processes determined by the state of the art and a machine park's manufacturing capacity. The second research field (P) is determined by the expected functional and usable properties resulting from the client's demands and concentrates on the product and the material it is made of. The experts were evaluating the occurrence probability of the relevant scenarios by dividing the total value of probability (of 100%) by the three possible variants of future events. The (output) dependent variables represent a probability that each of the three macroscenarios considered, i.e. optimistic, neutral and pessimistic, occurs. The types of the scenarios created and their links to neural networks are presented in Fig. 4.

A project of artificial neural networks and their numerical simulation was prepared with Statistica Neural Networks software, 4.0F version. The following parameters were defined to create a calculation model using an artificial neural network: neural network types, neural network structures, error functions, activation functions, postsynaptic potential (PSP) functions, training methods and parameters, variables scaling methods. The type of a neural network is defined with a mathematical neuron model and also with the characteristic arrangements of neurons in the network and also with the method of links between neurons, as discussed in the following publications [23-27]. General regression neural networks (GRNN)

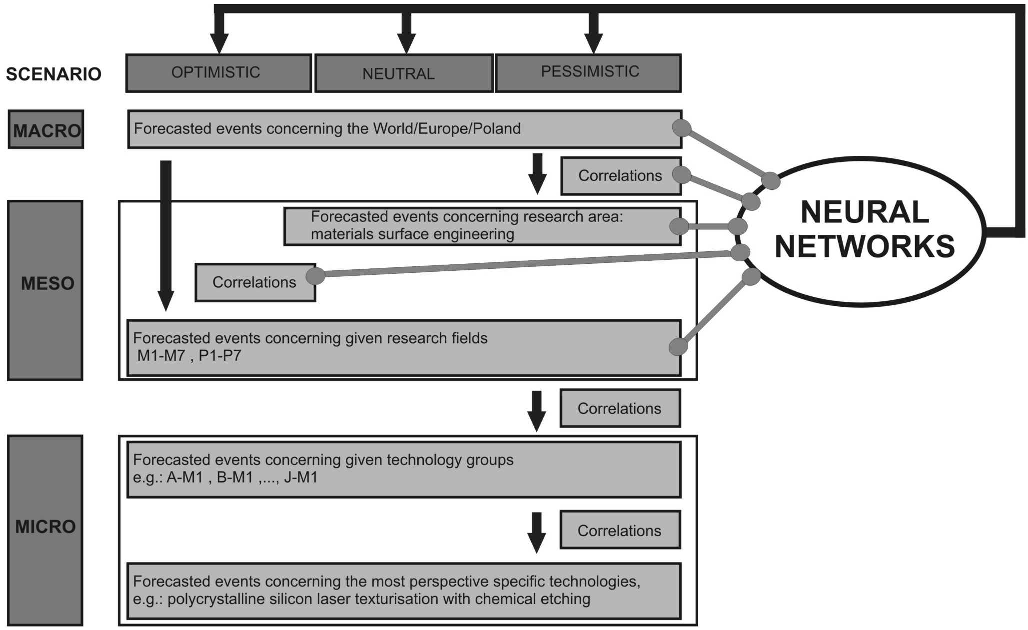


Figure 4. *The types of the scenarios created versus neural networks*

are made up of four layers: an input, radial, regression and output layer. Radial neurons, the number of which equals the number of patterns, represent the centres of concentrations existing in the training set. The regression layer, made up of linear neurons, has one neuron more than the output layer. The neurons of this layer fulfil two tasks: the first task – fulfilled by the neurons the number of which corresponds to the number of the network outputs, calculate conditional regression for each output variable, the second task – fulfilled by a single neuron, comes down to calculating the density of probability [28, 29]. Each of the neurons of the output layer designates a quotient of conditional regression calculated for a neuron of the preceding layer and for the density of probability. Neural networks with radial base functions (RBF) have three layers: an input layer, a hidden layer with radial neurons and an output layer with neurons having a linear characteristic. Linear neural networks (LNN) have two layers only: an input and output layer. Information is processed in the output layer only. The output layer has a linear PSP function and a linear activation function. The most popular type of neural networks is a multilayer perceptron (MLP). A linear postsynaptic potential function and usually a nonlinear activation function are used for such type of neural networks. Determining the number of hidden layers and the number of neurons in such layers is essential for designing the structure of multilayer perceptron [30, 31]. Table 2 lists the types of neural networks analysed in the chapter and their corresponding characteristic values of future parameters.

Table 2. *The parameters optimised when designing neural networks*

Network type	Training method	Activation function	PSP function	Error function
LNN	pseudoinversion	Linear	linear	sum of squares
RBF	k-average, k-nearest neighbours, pseudoinversion	linear, linear saturation, exponential	linear, radial	
GRNN	sampling	exponential, linear saturation	quotiential, radial, linear	
MLP	reverse error propagation, conjugated gradients, quasi-Newton, Levenberg-Marquardt, fast propagation, delta-bar-delta	logistic, linear with saturation, hyperbolic	linear	

Artificial neural networks allow for the building of relations between the investigated values without defining a mathematic description of the problem analysed. It is essential to prepare a representative set of experimental data. The special cases of neural networks analysed in the training process should be distributed equally across the whole domain of the function approximate [32]. An important thing is to define the variability range of the data analysed, thus defining a space in which a neural network can be used. Extrapolation beyond the range of training data may lead to significant prediction errors. The fact that single values exist only within certain ranges of input variables does not allow to make an assumption that the neural model prepared will be correctly predicting the value of a dependent variable in the area defined by the minimum and maximum values of the relevant independent variables. Whilst analysing the results of the survey investigations, special attention was paid to untypical, rare data. Those answers of the experts identifying the occurrence probability of a growth trend, stabilised trend or falling trend, clearly differing from the information provided in the other surveys, were analysed. The evaluation was made using the size tables prepared for independent variables. 5 and 95 percentiles were determined for each variable input. The range of independent variables was thus designated for which a neural model can be used. A few dozens of neural networks differing by their type (GRNN, RBF, MLP, LNN), structure, error and activation functions, training method and parameters were analysed for each model. Information on the neural networks characterised by the most favourable values of the indices used for the evaluation is listed in the table. Table 3 gives an example of such a list prepared for an optimistic scenario applying to the research field (P).

***Table 3.** Overview of artificial neural networks: research field (P), optimistic scenario*

Network symbol		**3.2P_1**	**3.2P_2**	**3.2P_3**	**3.2P_4**	**3.2P_5**
Type of network / number of neurons in layers: input-hidden-output		MLP/ 21-5-1	MLP/ 21-6-1	**MLP/ 21-7-1**	MLP/ 21-9-1	MLP/ 21-11-1
Training method / number of training epochs		BP/50, CG/2	BP/50, CG/130	**BP/50, CG/132**	BP/50, CG/33	BP/50, CG/273
Average absolute error, %	training set	7.5	6.3	**6.3**	7.0	5.7
	validating set	7.5	6.2	**6.4**	6.7	5.2
	testing set	7.9	7.0	**6.5**	6.8	5.5
Standard error deviation, %	training set	9.8	8.4	**8.0**	9.4	7.3
	validating set	10.2	8.9	**9.8**	9.1	8.0
	testing set	9.7	8.9	**7.9**	8.5	7.1
Correlation coefficient	training set	0.45	0.63	**0.68**	0.51	0.74
	validating set	0.43	0.62	**0.6**	0.59	0.71
	testing set	0.48	0.59	**0.69**	0.63	0.78

Explanations:
Amount of data in the training / validating / testing set: 150 / 35 / 35
Error function: sum of squares
Activation function in the input/ hidden/ output layer: linear saturation function/ logistic function / linear saturation function
Post Synaptic Potential (PSP) function: linear function
BP: Error back propagation method
CG: Conjugate gradient method
(shaded) Neural network chosen for further analysis

After completing the stage of designing and of numerical verification of artificial neural networks including calculations for a test set, a computer simulation of the impact of the trend change occurrence probability in the analysed thematic area on the macroscenario forecast was performed. The neural models developed were also used to calculate the values of independent variables for which each of the macroscenarios considered should assume the defined value. As there was no mathematical model describing the process examined and as there was relatively large space for potential solutions, it was decided that random activity will be the appropriate approach to solve the issue analysed. According to the general definition, any techniques employing random variables to solve a problem are called Monte Carlo methods [33]. If the issue is analysed in more detail, the Monte Carlo name often refers to a group of methods having the following common characteristics: they analyse a specific and finite space of considerations, they determine points randomly from the area of input data and for each of them. In addition, due to clear calculation procedures, partial results are obtained and they determine the ultimate result by aggregating partial results [34]. The adopted calculation method of independent variables, for which each of the considered macroscenarios should assume a set value, has the characteristics mentioned above. It should therefore be said that

Monte Carlo methods have been used to solve the research problem. The random sampling of the area in many cases improves a chance of obtaining a suboptimum solution which is a sufficient outcome from the user's prospective. As the number of tests increases, so increases the probability of designating a vector of input variables for which the concept examined assumes optimum values. The detailed stages of implementing neural networks in e-foresight research are shown in Fig. 5.

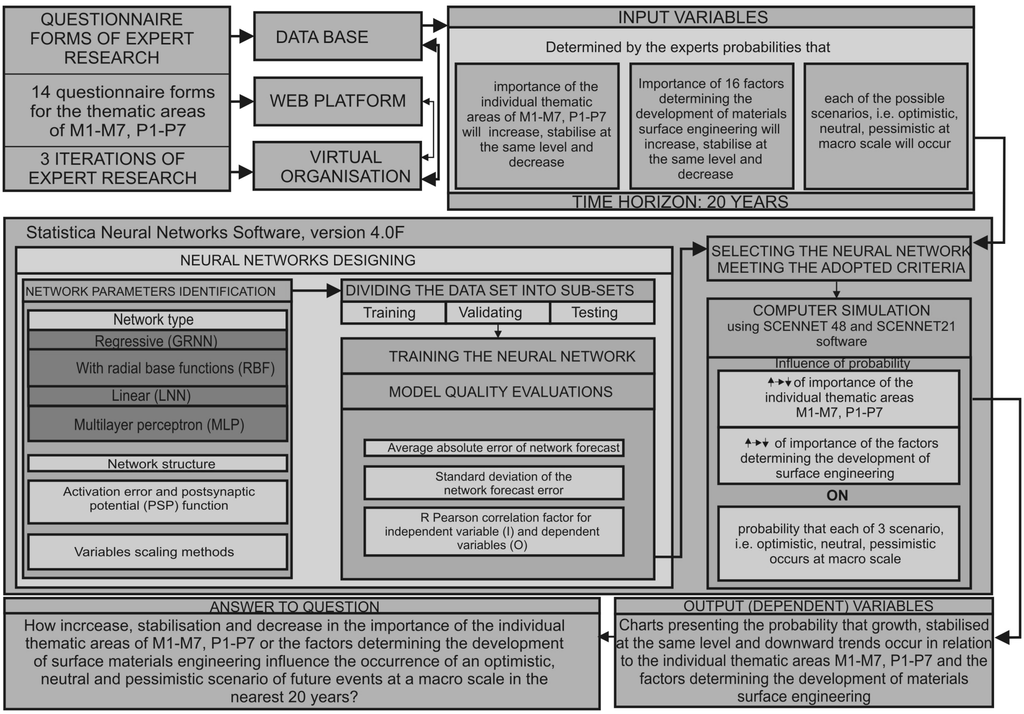


Figure 5. *Detailed stages of implementing neural networks in e-foresight research*

3.2. Computer simulations

The custom-designed SCENNET software available in two versions: 21 and 48, is an IT tool used for the determination of cross relationships and cause and effect relationships between the events likely to occur in the future at a macro- and mesoscale using neural networks. SCENNET21 enables to simulate the influence of development of the individual thematic areas of materials surface engineering on each of the three scenarios at a macroscale using neural networks and to present the simulation results in a table and in a graphical manner. SCENNET48 enables to simulate the influence of the key mesofactors conditioning the future development of materials surface engineering on each of the possible macroscenarios. A simulation based on neural networks is performed also in this case and the simulation results are generated as tables with numbers and as charts showing graphically a probability that the relevant trends of the analysed factors occur.

The task of SCENNET21 software is to find optimum input parameters in order to obtain the set output value for the selected neural networks. The programme was created using C++ language with the C++Builder XE2 Professional packet. It enables to search a maximum output value, minimum output value and a value set by the user and to find optimum values for one of 6 neural networks prepared with Statistica Neural Networks 4.0F software. The networks were implemented using C++ language and were incorporated into the software as functions. Each of the functions assumes as input parameters a table consisting of 21 elements representing input variables of the selected neural network. A number representing an output variable of the neural network is the result of each of such functions. A set of 21 input parameters is divided into seven groups each containing three elements. Each of the groups corresponds to a single analysed thematic area, respectively between M1 to M7 and between P1 to P7, depending on the network selected. Three elements inside the group mean, respectively: a probability that a growth trend occurs, a probability that a stabilised trend occurs at the existing level and a probability that a falling trend occurs for the individual groups of technologies in relation to the overall surface engineering technology. Each input parameter of the function may assume values ranging between 0 to 100. The programme enables to set a minimum and maximum search value individually for each input variable. A sum of three probabilities of the occurrence of the individual trends must equal 100. Approx. 5000 combinations meeting the condition of the sum of three probabilities equal to 100 is obtained for the range of 0 to 100 for each thematic area. Due to a very high number of possible combinations a random search method (Monte Carlo) was applied. It takes on average 200 ms to check the 10^4 combinations. An increase in computation time according to the number of iterations is presented on the chart (Fig. 6). Time measurements were made with a computer equipped with an Intel Core i5 M560 2.67Ghz CPU and 4 GB RAM memory. A collection of solutions approximate to optimum solutions is obtained after checking about

10^7 iterations. The subsequent iterations have a minimum impact on the improvement of the results obtained, therefore it is groundless to perform them considering that the time necessary for performing them is rising exponentially.

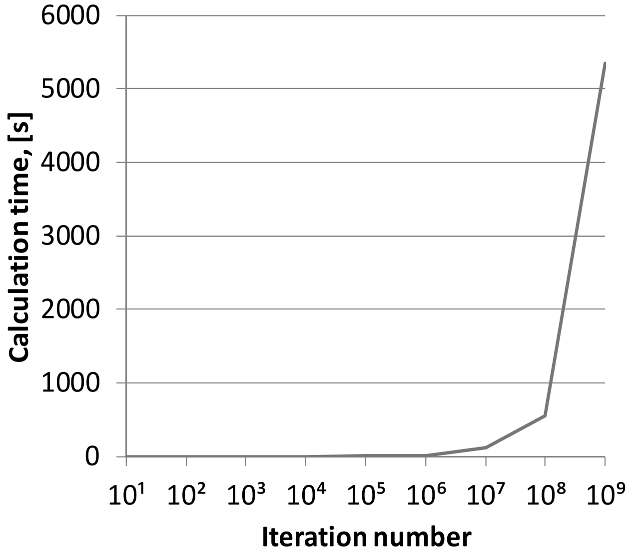


Figure 6. *Chart illustrating dependency between computation time and the number of iterations performed*

The working principle of SCENNET21 software is shown in a flow chart presented in Fig. 7. The user sets search parameters in the first place, including: the number of solution search iterations, the network to be the objective function, the ranges of input variables and the value expected for a network output variable. The programme, using the input data entered, calculates the width of search ranges and then all the possible combinations of probabilities for each thematic area giving the sum of 100. The simulations are performed by assuming that the search area for the values of decision variables will be limited to the scope of changes defined in the constraints of neural models. Another step is to sample seven combinations of probabilities recorded in the previous step. A function representing a neural network is next activated where the input parameters are the seven combinations of the numbers sampled in the previous step. A network output value is recorded in the "store" table. The worst value is then removed from the "store" table. The previous four stages are repeated until the loop counter equals the number of iterations pre-defined by the user. Once the calculations are completed, the results are shown as tables. The results can be exported to a spreadsheet (a file with csv extension) and can be presented as charts recorded as a graphical file with svg extension. The programme additionally features a function of generating chart labels in Polish and English and is recording charts in the colour and monochromatic version.

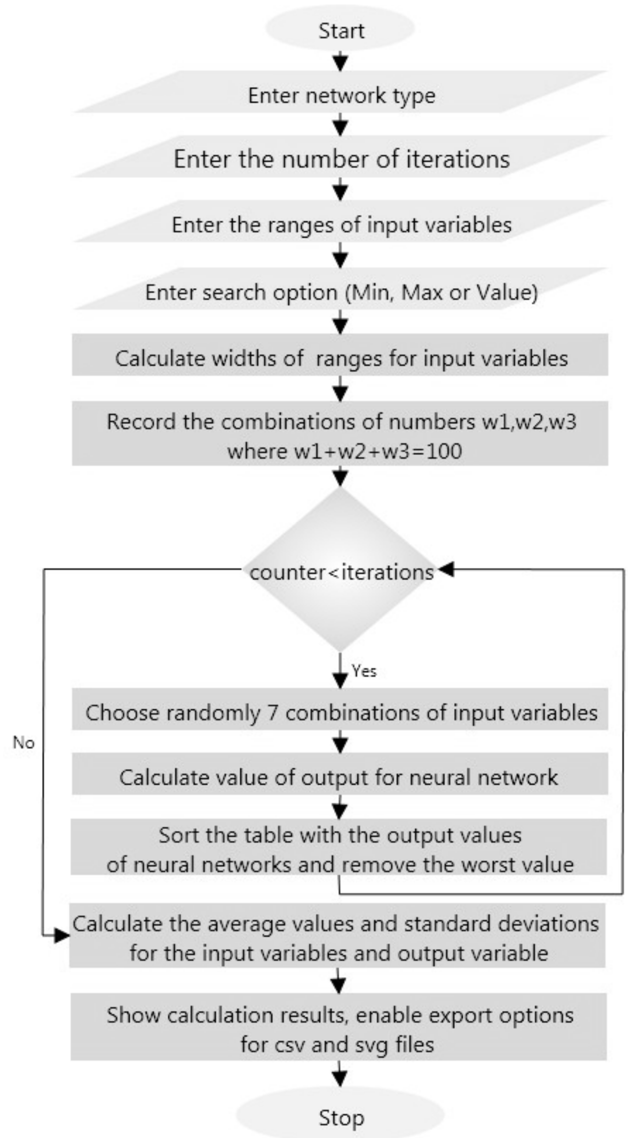


Figure 7. *SCENNET21 software flow chart*

A modification of SCENNET21 software is SCENNET48 software using its motor. SCENNET48 software calculates optimum values for the subsequent three neural networks to identify which of the mesofactors determining the future development of materials surface engineering (e.g. collaboration between science and industry, the number of specialised laboratories and R&D institutions, continuous improvement and high quality of technology, transparent and friendly legislation, international co-operation and EU funds). The subgroup elements, similar as in SCENNET21 software, specify the subsequent probabilities that the relevant trends occur, the sum of which needs to be equal to 100. The programme working algorithm differs in the number of the combinations of the probabilities sampled. The results of calculations are presented as a table. SCENNET48 software features the same export options as its predecessor. Fig. 8 shows an example of a window of SCENNET48 showing parts of calculations carried out for an optimistic scenario with a 20% probability defined by the user and the number of iterations equal to 100 000.

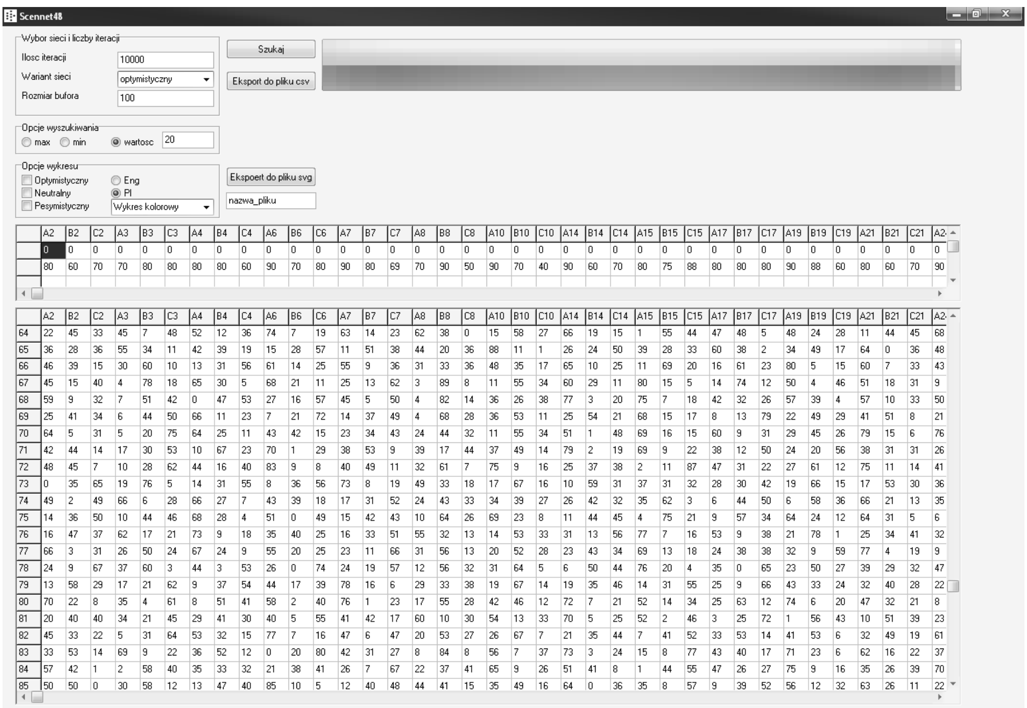


Figure 8. *Examples of SCENNET48 software window presenting the results of a simulation made using neural networks*

The purpose of the computer simulations performed using SCENNET21 software was to present to what degree the development of the individual thematic areas forming part of the research field (M) Manufacturing and (P) Product influences the occurrence, with a specific probability, of one of the three scenarios. A representative chart for the research field (M) generated by SCENNET21 software for an optimistic scenario which, according to the experts, can occur with a probability of 30%, is shown in Fig. 9. Probability that a growth trend, a trend stabilised at the current level and a falling trend occurs was determined on the axes of abscissa in percents. The relevant, analysed thematic areas are provided on the axis of coordinates, i.e., respectively: (M1) Laser technologies in surface engineering, (M2) PVD technologies, (M3) CVD technologies, (M4) Thermochemical technologies, (M5) Polymer surface layers, (M6) Nanostructural surface layers, (M7) Other surface engineering technologies. The results presented of a computer simulation performed using neural networks indicate that the following, respectively, has a substantial positive impact on the development of materials surface engineering in general and the implementation of an optimistic macroscenario likely to occur with a 30% probability: Nanostructural surface layers (M6), Laser technologies in surface engineering (M1), PVD technologies (M2) and the Polymer surface layers (M5). The same results for the second research field of (P) Product are shown in Fig. 10. The following thematic areas are provided on the axis of coordinates, respectively: (P1) Surface engineering of biomaterials, (P2) Surface engineering of structural metallic materials, (P3) Surface engineering of structural non-metallic materials, (P4) Surface engineering of tool materials, (P5) Surface engineering of steels used in automotive industry, (P6) Surface engineering of glass, micro- and optoelectronic and photovoltaic elements, (P7) Surface engineering of polymers. The results of the simulation made indicate that the following have the largest positive impact on the development of materials surface engineering in general and on the implementation of the optimistic macroscenario that occurs with a 30% probability, respectively: Surface engineering of, respectively: (P6) glass, micro- and optoelectronic and photovoltaic elements, (P1) biomaterials and (P4) tool materials.

The simulations aimed at determining to what degree the selected critical mesofactors impact the occurrence, with a specific probability, of one of the three macroscenarios, were carried out with SCENNET48 software. The results of the computer simulations carried out with neural networks point out that the following factors have mainly a considerable, positive impact on the development of materials surface engineering in general and on the implementation of the optimistic macroscenario that may occur with a 30% probability. The factors include: collaboration between science and industry and the growing importance of nanomaterials and graded materials in relation to other materials surface engineering technologies; the number of specialised laboratories and R&D institutions; continuous improvement and high quality of technology; transparent and friendly legislation; international co-operation and EU funds as well as the rising significance and strengthening of the technologies ensuring mechanical, tribological and anticorrosive properties.

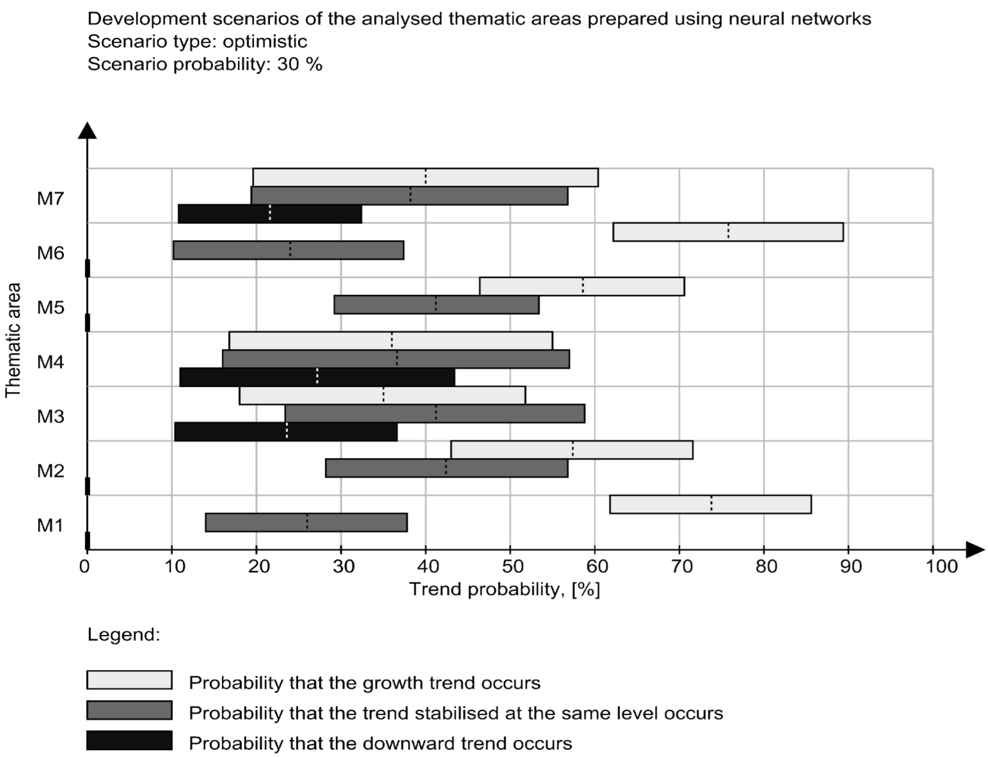


Figure 9. *Results of simulations that use neural networks, presenting the probability values for the occurrence of an increase, stabilised and decrease trend for the thematic areas of the (M) research field if the optimistic scenario takes place with a 30% probability*

The experiments made have shown that it is substantiated to use neural networks for analysing cross impacts between events when creating the multi-variant probabilistic scenarios of future events. By using this simulation tool, a dependency can be identified between the occurrence, with a specific probability, of each of the considered alternative macroscenarios and the variants of changing the individual mesofactors while taking into account that within the defined time horizon they can increase, remain stable or decrease. All the difficulties encountered by pioneers have been related to the experimental and innovative idea of implementing neural networks for creating the scenarios of future events. The chief challenge was the specificity of the input data in form of expert opinions expressed quantitatively with the universal scale of relative states. The phenomena were assessed differently because such assessment tends to be subjective, which is typical for expert investigations. In particular the experts, most likely unintentionally, on one hand were making an attempt to represent the interests of their own circles and on the other hand were frequently viewing those phenomena having a high level of generality (macro- and mesoscale) through the prospective of their own, much narrower, specialisation.

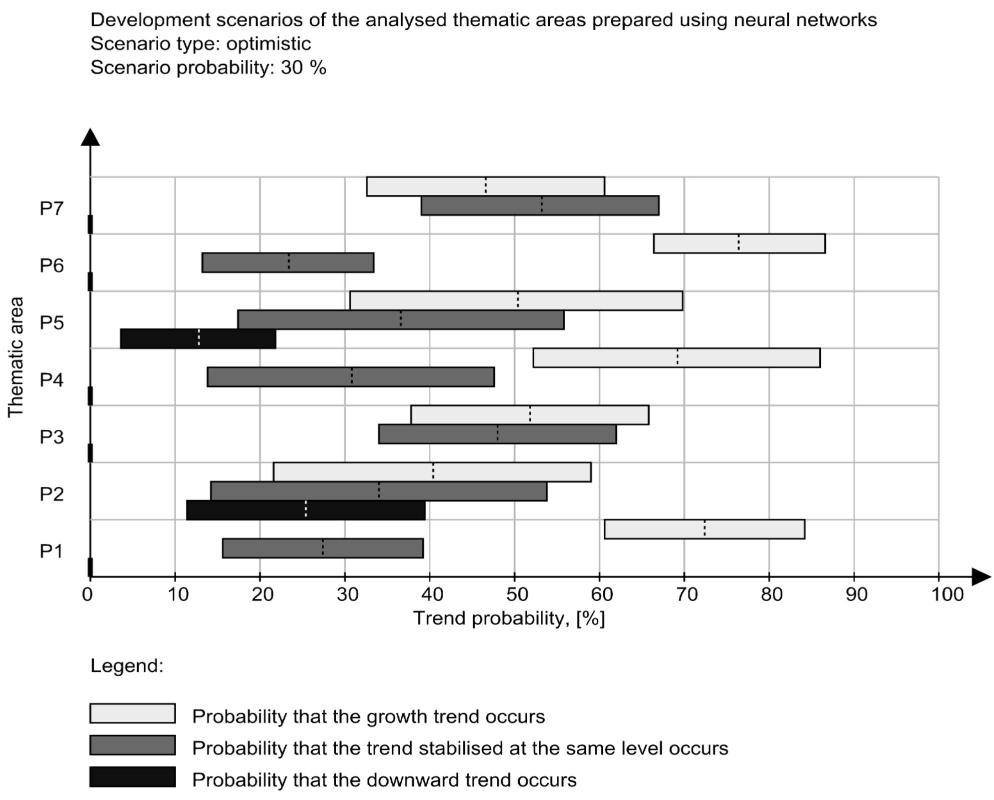


Figure 10. *Results of simulations that use neural networks, presenting the probability values of the occurrence of an increase, stabilised and decrease trend for the thematic areas of the (P) research field if the optimistic scenario takes place with a 30% probability*

4. Forecasted laser surface treatment progress

The anticipated development and strategic position of laser technologies in respect of materials surface engineering was identified using the reference data acquired whilst performing technology foresight for materials surface engineering [6]. Over 300 independent experts from many countries representing scientific, business and public administration circles have taken part in the FORSURF technology foresight. The experts have completed approx. 650 multi-question surveys and held thematic discussions during 10 expert panels. A collection of 140 critical technologies, 10 for each thematic group, was selected for the above 14 thematic groups from the initially inventoried approx. 500 specific technology groups. The scientific and research methods of evaluating the state of the art for a particular concept, technology review and a strategic analysis with integrated methods were used for this purpose, including: extrapolation of trends, environment scanning, STEEP analysis, SWOT analysis, expert panels, brainstorming, benchmarking, multi-criteria analysis, computer simulations and modelling, econometric and static analysis. 10 critical technologies were selected within the group of 14 thematic areas as a result of the efforts undertaken. A collection of 140 critical technologies was thoroughly analysed according to three iterations of the e-Delphix method performed according to the idea of e-foresight [35]. Laser technologies in surface engineering was one of the 14 thematic areas analysed as part of the foresight research.

Foresight investigations with the sample size of 198 have revealed a very robust strategic position of laser technologies among other materials surface engineering technologies. The experts found that that laser technologies have the best industrial application prospects in the group of all the analysed materials surface engineering technologies in the nearest 20 years. 78% of the surveyed held such a view. Nearly a three fourth of the respondents (73%) maintain that numerous scientific and research studies will be devoted to such technologies in the analysed time horizon. 70% of the persons surveyed claim that the thematic area of “Laser technologies in surface engineering” is crucial and its importance should be absolutely rising so that an optimistic scenario can come true of the country’s/Europe/World development, i.e. “Race won” assuming that the potential available is adequately utilised to fulfil the strategic objectives of development and so that people, statistically, are better off, social attitudes are optimistic and the prospects for the coming years bright. 81% of the surveyed persons argue that the significance of laser technologies in relation to other materials surface engineering technologies will be growing, whereas 18% maintain it will remain on the same level with only

3 individuals asserting that the role will diminish over the next 20 years. The excellent results of technology foresight elaborated based on the reference data point to, therefore, the anticipated key role of laser technologies for the advancement of the overall materials surface engineering (mesoscale) and for the development of the entire domestic/ European/ global economy (macroscale) [18] The described technology foresight outcomes prepared based on the opinions of the experts expressed during the research with the e-Delphix method presenting a position of laser technologies against materials surface engineering in general are shown in Fig. 11.

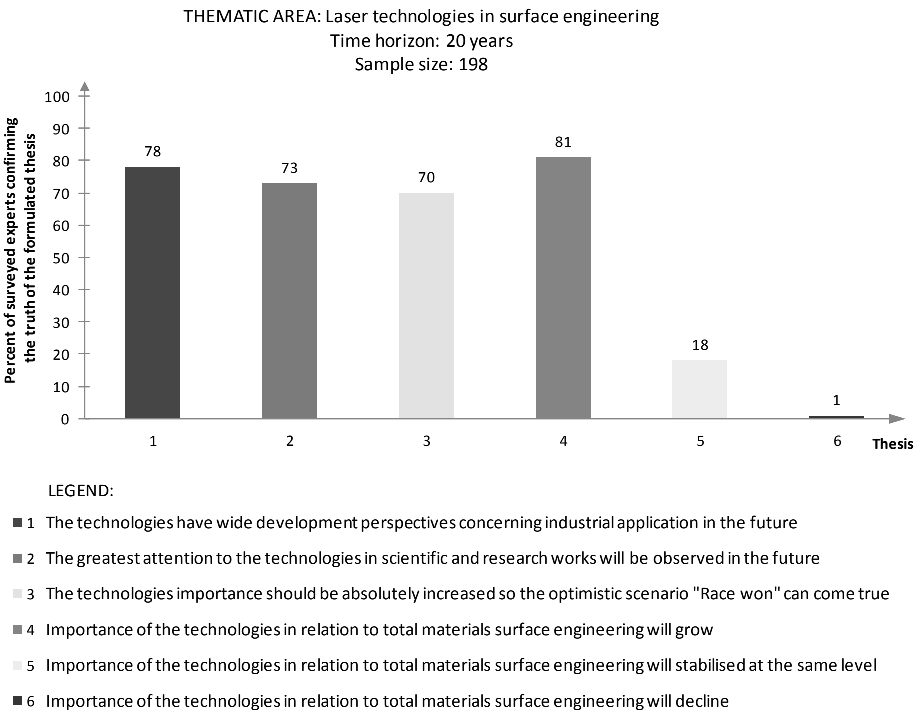


Figure 11. *Strategic position of laser technologies versus other materials surface engineering technologies*

5. Strategic position of critical laser technologies in surface engineering

A state of the art analysis undertaken in the initial stage of the foresight research including a diagnosis of the state of the art, technology review and a strategic analysis with integrated methods enabled to choose 10 critical technologies for each of the 14 thematic areas analysed, including the area of "Laser technologies in surface engineering". Critical technologies should be understood as priority technologies with the best development outlooks and/or of key significance for the industry within the analysed time horizon of 20 years. The data required for determining development tendencies and a strategic position of the individual groups of critical technologies for laser surface treatment was acquired via electronic surveys completed by the experts. The surveys were prepared using the e-Delphix method according to the guidelines of e-foresight [35]. A selected group of the key experts being specialists in the field of laser technologies assessed the relevant groups of critical technologies according to a universal scale of relative states where 1 is a minimum rate and 10 an extraordinarily high one. A set of unprocessed primary data was analysed. The analysis results were shown graphically using a pool of foresight matrices [36]. The following groups of critical technologies of laser surface treatment were examined in particular:

(A) Laser heat treatment,
(B) Laser remelting,
(C) Laser alloying / cladding,
(D) Laser cladding,
(E) Laser additive manufacturing (e.g. LENS),
(F) Laser Chemical Vapour Deposition (LCVD),
(G) Laser Assisted Physical Vapour Deposition (LAPVD),
(H) Laser treatment of functional materials (e.g. polycrystalline laser texturing in photovoltaics),
(I) Pulsed Laser Deposition (PLD),
(J) Laser treatment of biomaterials.

According to the methodology established, a strategic position of each of the analysed critical technologies of laser surface treatment is presented graphically using the matrix of strategies for technologies made up of sixteen fields. The matrix presents, graphically, a position of each group of technologies according to its value and environment influence intensity and identifies a recommended action strategy. The matrix contains the results of the expert investigations visualised with the dendrological and meteorological matrix transformed by means of software created for this purpose. The methodological structure of the both matrices is referring to the portfolio methods commonly known in management sciences, and first of all to the BCG matrix [37], enjoying its unique popularity due to a reference to simple associations and intuitive reasoning, becoming an inspiration when elaborating methodological assumptions for the both matrices. A four-field dendrological matrix of the technology value includes the expert assessments for the relevant technologies according to the potential being the actual objective value of the specific technology group and according to attractiveness reflecting the subjective perception of the relevant technology group by its potential users. A four-field **matrix of environment influence** presents, in a graphical manner, the results of how the external positive (opportunities) and negative (difficulties) factors influence the technologies analysed [36].

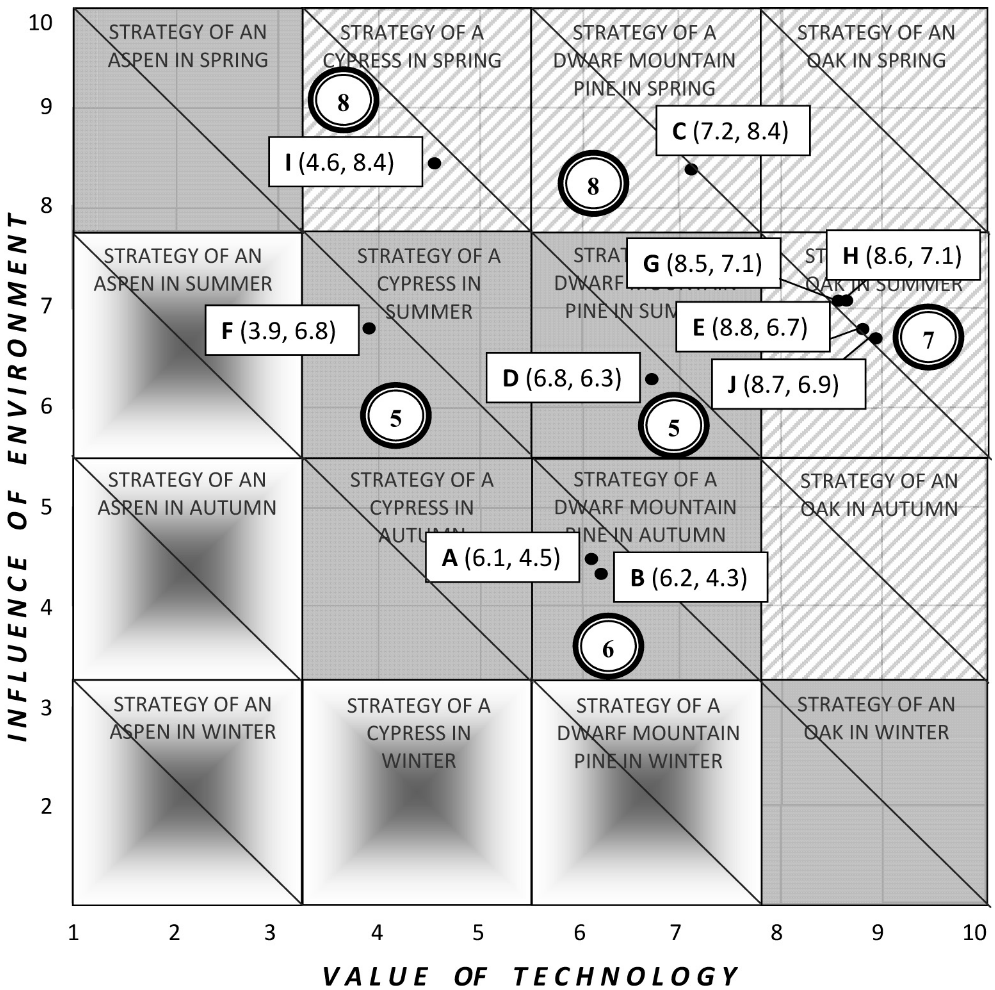


Figure 12. *A matrix of strategies for technologies prepared for the thematic field of "Laser technologies in surface engineering"*

A matrix of strategies for technologies developed for the thematic area of "Laser technologies in surface engineering" is provided in Fig. 12. The circles mark the strategic development prospects of a given group of technologies expressed in numbers using the universal scale of relative states.

The development outlooks of the technology group (C) corresponding to laser alloying / cladding was highly evaluated in a ten-degree scale, by awarding 8 points. The technology group (C) was placed in the dwarf mountain pine in spring field signifying its high potential and limited attractiveness. It is hence recommended for the group to make the technology more attractive, more modern, to automate it, to computerise it and to promote it using the strong market conditions. Pulsed Laser Deposition (I) also was awarded 8 points and was placed in the cypress in spring field meaning that this technology group is highly attractive and its potential needs to be strengthened. For this purpose, the technology has to be researched, improved and invested in further in the strong market conditions. As regards the very promising experimental or prototype technologies that were given 7 points, i.e. laser treatment of functional materials (H) and biomaterials (J) and Laser additive manufacturing (E) and also Laser Assisted Physical Vapour Deposition (G) being in their early-mature phase of the lifecycle, the oak in summer strategy is recommended. The strategy provides that the technology's attractiveness and potential should be exploited in the risky environment of fierce global competition. In addition, opportunities should be sought for and difficulties avoided and the technology should be intensively promoted with such measures being preceded by marketing research in order to tailor the product to a customer's demands as far as possible. The development prospects of the base groups of technologies, i.e. (A) laser heat treatment and (B) laser remelting were found to be moderate (6). It was recommended that profits should be derived from production conducted in a stable, predictable environment using a robust technology that should be modernised and intensively promoted to enhance its appeal. The group of the base technologies (D) of laser cladding was placed in the field of the dwarf mountain pine in summer, and the action recommended for the technology is to make this technology, having a large potential, more attractive and modern and to tailor the technology to a client's requirements according to the results of marketing research. Laser Chemical Vapour Deposition (F) was placed in the cypress in summer field implying that the potential of this attractive technology group should be enhanced in the risky conditions of the environment and that the risk should be appraised and, depending on the outcome, either a customer should be aggressively fought for or the technology should be phased out from the market slowly. The environment of the base group of technologies (D) and of the early-mature group of technologies (F) is a stormy one, therefore, one should not preclude that either positive or negative surprise scenarios of their development should take place.

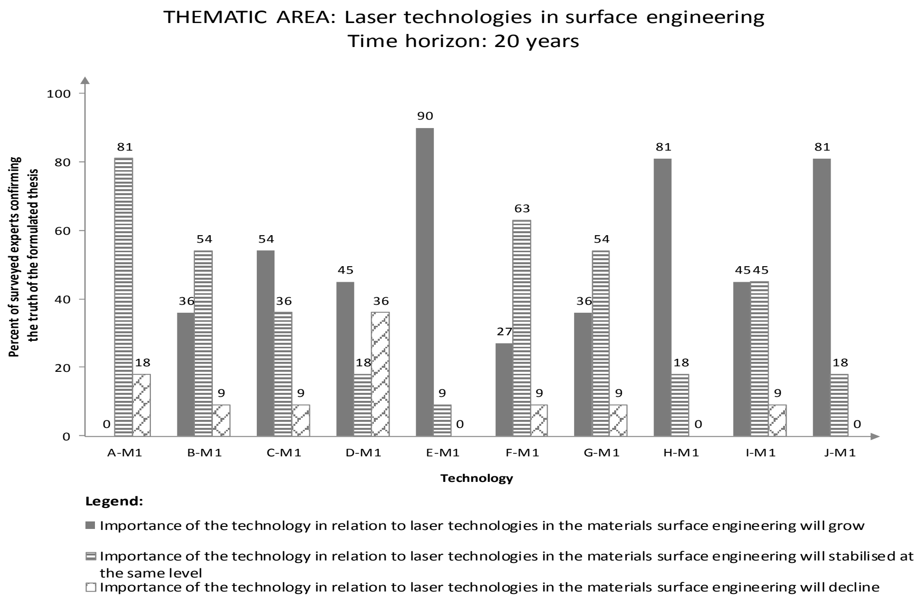


Figure 13. *Expert opinions presenting the expected increase, stabilisation and decrease in the importance of the individual groups of critical laser surface treatment technologies in relation to the thematic area of "Laser technologies in surface engineering"*

The experts surveyed, as part of the research conducted with the e-Delphix method, also identified the forecast development trends of the relevant critical technologies of laser surface treatment against the thematic area of "Laser technologies in surface engineering". Laser additive manufacturing (E), the importance of which against other laser surface treatment technologies should be rising according to 90% of experts, was ranked highest. Pulsed Laser Deposition (I) and laser treatment of biomaterials (J) also enjoyed high rates. 81% of the experts claim that the importance of those groups of technologies will be growing over the nearest 20 years. The statement presented shows that the future of laser cladding (D) is most uncertain as 36% of the experts maintain that the role of this technology group will be dwindling, 45% of them think the role will be on the rise and 18% assert that the role will maintain at the same level. Fig. 13 lists in detail all the expert opinions reflecting the anticipated growth, stabilisation and decline in the importance of the relevant groups of critical laser surface treatment technologies with respect to the thematic area of "Laser technologies in surface engineering".

6. Hot-work steels laser treatment today and in the future

6.1. Materials and methodology

The long-run development prospects of hot-work alloy tool steels subjected to laser treatment using the custom methodology [36] were identified based on interdisciplinary research including materials science experiments, notably light and scanning microscopy, X-ray phase qualitative analysis and investigations into mechanical and functional properties (hardness, microhardness, roughness, wear strength, thermal fatigue strength) as well as expert studies. The samples of hot-work alloy tool steel X40CrMoV5-1 and 32CrMoV12-28 with their chemical composition given in Table 4 were used for own investigations. The samples underwent typical heat treatment, i.e. they were quenched and tempered twice, and then remelted (without using powders) and laser alloyed. Carbide powders with their properties listed in Table 5 were deposited onto the samples prior to laser alloying. Fig. 14 shows a photo of one of the powders used for alloying, i.e. tungsten carbide WC. A ROFIN SINAR DL 020 High Power Diode Laser (HPDL) was applied for the laser remelting and alloying of the steels with carbide powders. The technical specifications of the laser are given in Table 6. Six homogenous groups were distinguished between for the analysed technologies by using the type of powder deposited onto the surface or the lack of such powder as a comparative analysis criterion, including, respectively:

(K) Remelting of hot–work alloy tool steels (without powders),
(L) Alloying of hot–work alloy tool steels using the NbC niobium carbide,
(M) Alloying of hot–work alloy tool steels using the TaC tantalum carbide,
(N) Alloying of hot–work alloy tool steels using the TiC titanium carbide,
(O) Alloying of hot–work alloy tool steels using the VC vanadium carbide,
(P) Alloying of hot–work alloy tool steels using the NbC WC tungsten carbide.

Table 4. *Chemical composition of the examined hot-work alloy tool steels*

Steel grade	Mass concentration of elements, %								
	C	Mn	Si	P	S	Cr	W	Mo	V
X40CrMoV5-1	0.41	0.44	1.09	0.015	0.010	5.40	0.01	1.41	0.95
32CrMoV5-1	0.308	0.37	0.25	0.020	0.002	2.95	–	2.70	0.535

Table 5. *Selected properties of powders used for laser treatment*

Coating type	Hardness HV, GPa	Melting point, °C	Density, g/cm^3	Thermal expansion coefficient α, $10^{-6}\cdot K^{-1}$
WC	2400	2730-2870	15.77	23.8
NbC	1800	3480-3610	7.6	7.6
VC	2600	2650-2830	5.81	7.5
TiC	3200	3065-3180	4.94	8.3
TaC	1600	3780-3985	14.5	7.8

Table 6. *Technical data of HPDL ROFIN DL 020 diode laser*

Parameter	Value
Laser wave length, nm	940 ± 5
Power, W	100-2300
Focus length of the laser beam, mm	82/32
Power density range of the laser beam in the focus plane, kW/cm^2	0.8-36.5
Dimensions of the laser beam, mm	1.8-6.8 with 82 mm focus length

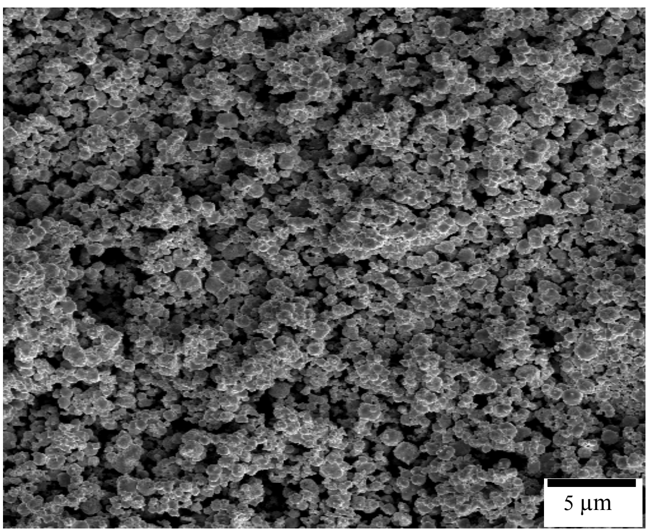


Figure 14. *Topography of the WC tungsten carbide powder used for steel alloying (SEM)*

The structure of the tested steels was observed with a Leica MEF4A light microscope with the magnification of: 25-1000 x and with a DSM-940 electron scanning microscope by Opton with the accelerating voltage of 20 kV. The structures were photographed with a Leica – Qwin computer-aided image analysis system and the following was measured: the depth of the remelted zone (RZ), of the heat-affected zone (HAZ) and the width of the bead appearance. Hardness measurements were taken with the Rockwell's method with a Zwick ZHR 4150TK hardness tester. The microhardness of the samples remelted and/or alloyed with laser was measured with the Vickers method with a DUH 202 Shimadzu ultramicrohardness tester. R_a, μm, roughness was measured with a Surtronic 3+ contact profilometer by Taylor - Hobson. The tests of abrasive wear resistance with the metal – ceramic material method were carried out using a specially constructed stand. Four remelting and/or alloying beads were made on each sample within the laser power range of 1.2-2.3 kW. Fig. 15 shows an example of a X40CrMoV5-1 steel view after alloying with tungsten carbide [38].

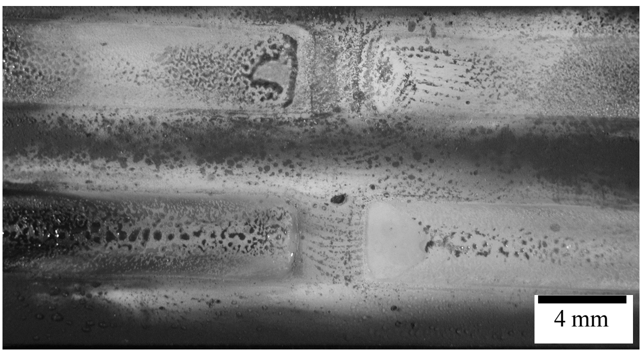


Figure 15. *View of the X40CrMoV5-1 hot-work alloy tool steel after alloying with the WC tungsten carbide, laser power of 1.2-2.3 kW*

The results of the strategic position evaluation for the relevant analysed technologies made according to the opinions of the key experts expressed with the universal scale of relative states (1 - min., 10 - max.) is presented in the graphical version with a set of foresight matrices [30]. The individual technologies, differing in the type of the powder deposited onto the substrate or the lack of it, were assessed for their potential and attractiveness. The results were placed into the dendrological matrix of the technology value. The results of the evaluation for the influence of external positive factors (opportunities) and negative factors (difficulties) on the technologies analysed were entered into the metrological matrix of environment influence.

The results of expert investigations were at the next stage of the works entered into the matrix of strategies for technologies presenting graphically the place, expressed in numbers, of each technology group considering its values and environment influence intensiveness and by indicating a recommended action strategy. Strategic development tracks according to three variants reflecting the predicted position of a specific technology for individual time intervals were also entered into the matrix. A group of technology roadmaps was established at the last stage of the works, based on the results of foresight-materials science research, being a graphical comparative analysis tool enabling to choose the best technology in terms of the materials science, technological or economic criterion selected.

6.2. Structure and properties of leaser treated hot-work steels

A remelted zone (RZ), heat-affected zone (HAZ) as well as transition boundaries between the remelted zone and the heat-affected zone and between the heat-affected zone and the native material are formed in each remelted and/or alloyed surface layer of the examined steels [39-41]. The examples of surface layers after alloying X40CrMoV5-1 steel with tungsten carbide with the laser power of 1.2 kW and 32CrMoV12-28 steel with the laser power of 2.0 kW are shown in Fig. 16 and Fig. 17. The thickness of the remelted zone and the heat-affected zone depends on the laser beam power. If the rate of alloying and the thickness of the alloying layer is constant, zone thickness increases along with higher laser power [42, 43]. The surface layer formed in the remelting process is characterised by lower roughness. An increase in surface and roughness irregularity was, however, found for the steel alloyed with carbide powders.

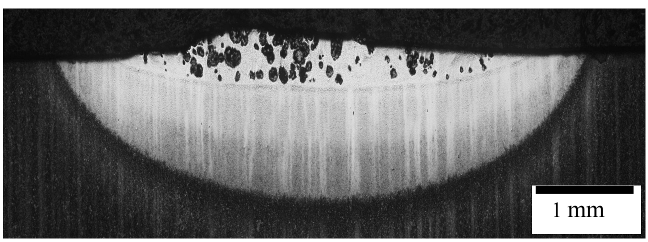
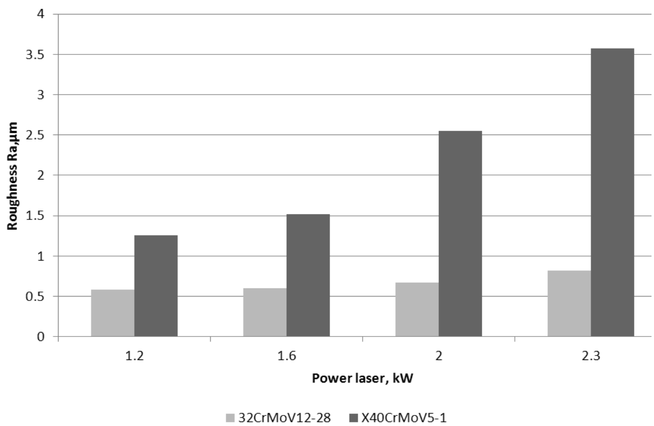


Figure 16. *Surface layer of the X40CrMoV5-1 steel after alloying with WC, the laser power of 1.2 kW*

Figure 17. *Surface layer of the 32CrMoV12-28 steel after alloying with WC, the laser power of 2.0 kW*

a)



b)

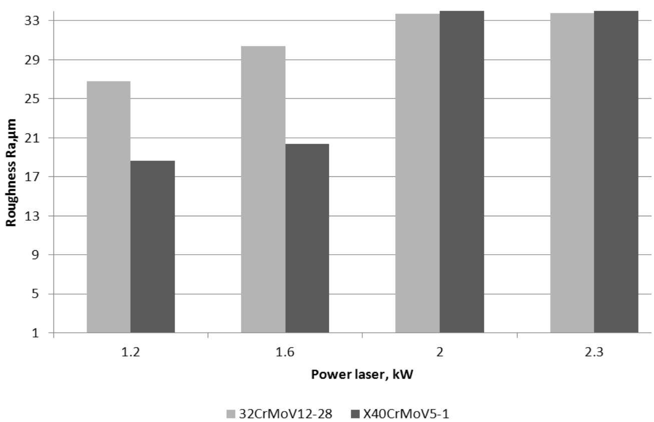


Figure 18. *Effect of laser power on the roughness of the X40CrMoV5-1 and 32CrMoV12-28 surface layers a) remelted with laser, b) alloyed with laser with the WC tungsten carbide; laser power of 1.2-2.3 kW*

This stems from the fact that the alloying material is fluctuating due to the varied surface tension of the material being remelted and by the laser radiation energy being absorbed by the alloying material. Fig. 18a shows how laser power influences the roughness of the remelted surface layers of the X40CrMoV5-1 and 32CrMoV12-28 steels, and Fig. 18b shows the same for those alloyed with tungsten carbide WC.

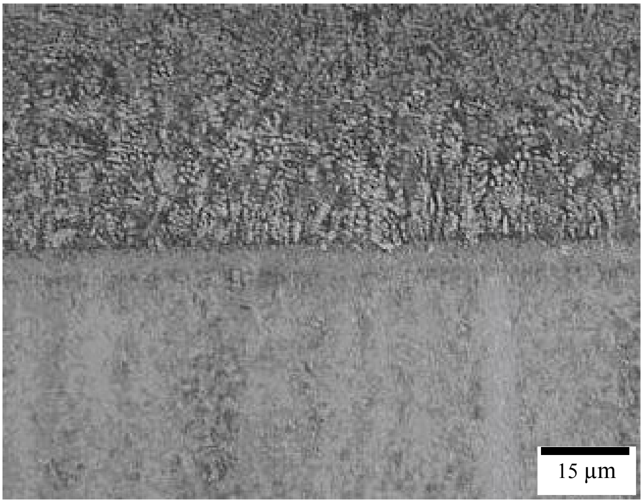


Figure 19. *Remelting toe of the X40CrMoV5-1 surface layer after the NbC niobium carbide alloying, laser power of 2.3 kW*

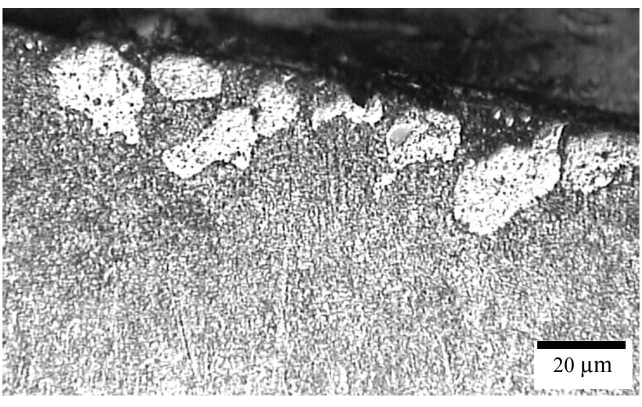


Figure 20. *Remelting limit of the 32CrMoV12-28 surface layer after the TaC tantalum carbide alloying, laser power of 1.6 kW*

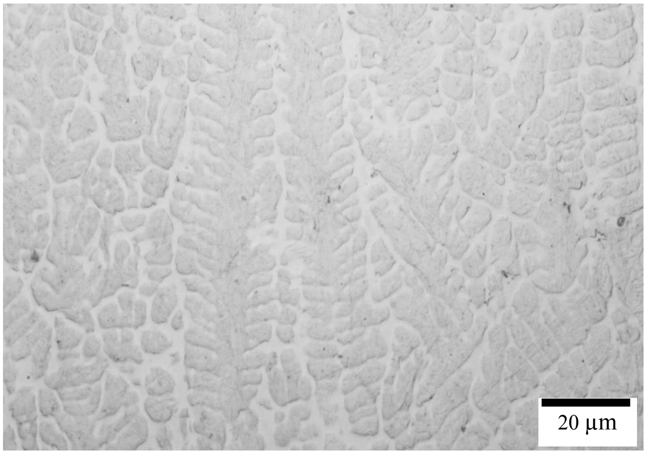


Figure 21. *Central zone of the X40CrMoV5-1 remelted surface layer after the TiC titanium carbide alloying, laser power of 1.2 kW*

It was found based on observations with a light microscope that the structure of steel after remelting and after laser alloying is characterised by the occurrence of areas with a highly varied morphology connected with material solidification. Heat in the central area of the remelted zone is evacuated in all directions and the structure thus formed is made of fine equiaxial crystals with a lattice of carbides [44-47]. Figs. 19-22 shows some examples of the remelting toe and the central zone of surface layer remelting for each of the steel grades analysed.

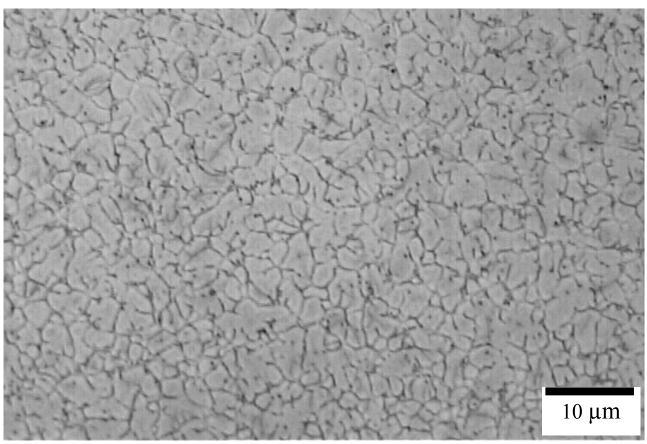


Figure 22. *Central zone of the 32CrMoV12-28 remelted surface layer after the VC vanadium carbide alloying, laser power of 2.0 kW*

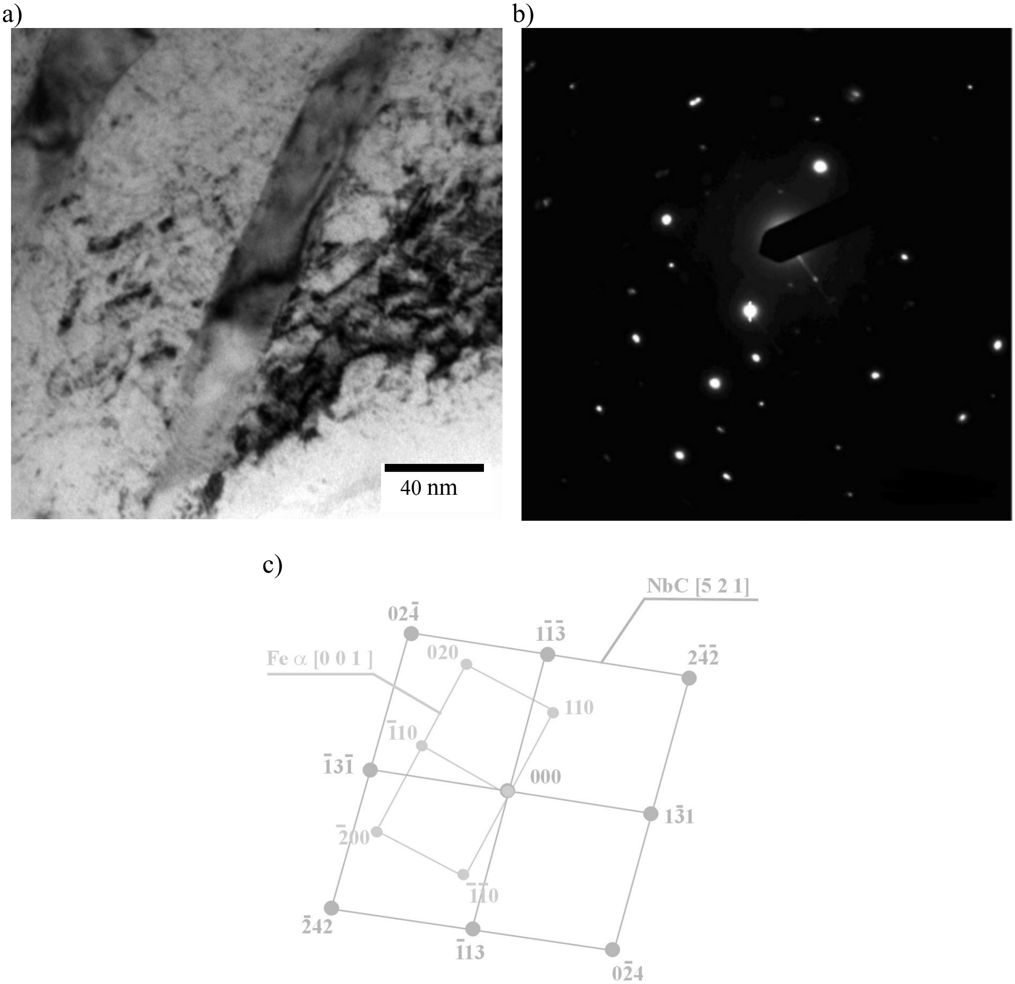


Figure 23. *Structure of thin foil made of the X40CrMoV5-1 steel after alloying with the NbC niobium carbide, laser beam power of 1.2 kW; a) image in bright field, b) diffraction pattern from the area as in figure a), c) diffraction pattern solution for figure b)*

It was found on the basis of investigations carried out for thin foils made of the X40CrMoV5-1 surface layer alloyed using laser with carbide powders that the relevant carbides used for alloying occur on the limits of grains (Fig. 23). Lath martensite with a high dislocation density constitutes the surface layer matrix after alloying [48, 49]. Fine carbides such as the M_3C or the M_7C_3 identified with the electrons diffraction method are also found in the martensite of the surface layer of the steel alloyed with laser [50, 51]. The investigations of thin foils made of the 32CrMoV12-28 laser-alloyed steel with carbide powders reveal the presence of the dispersive lattice of carbides, at the limits of grains mainly. They form as fine dispersive carbides in some cases inside the grains (Fig. 24).

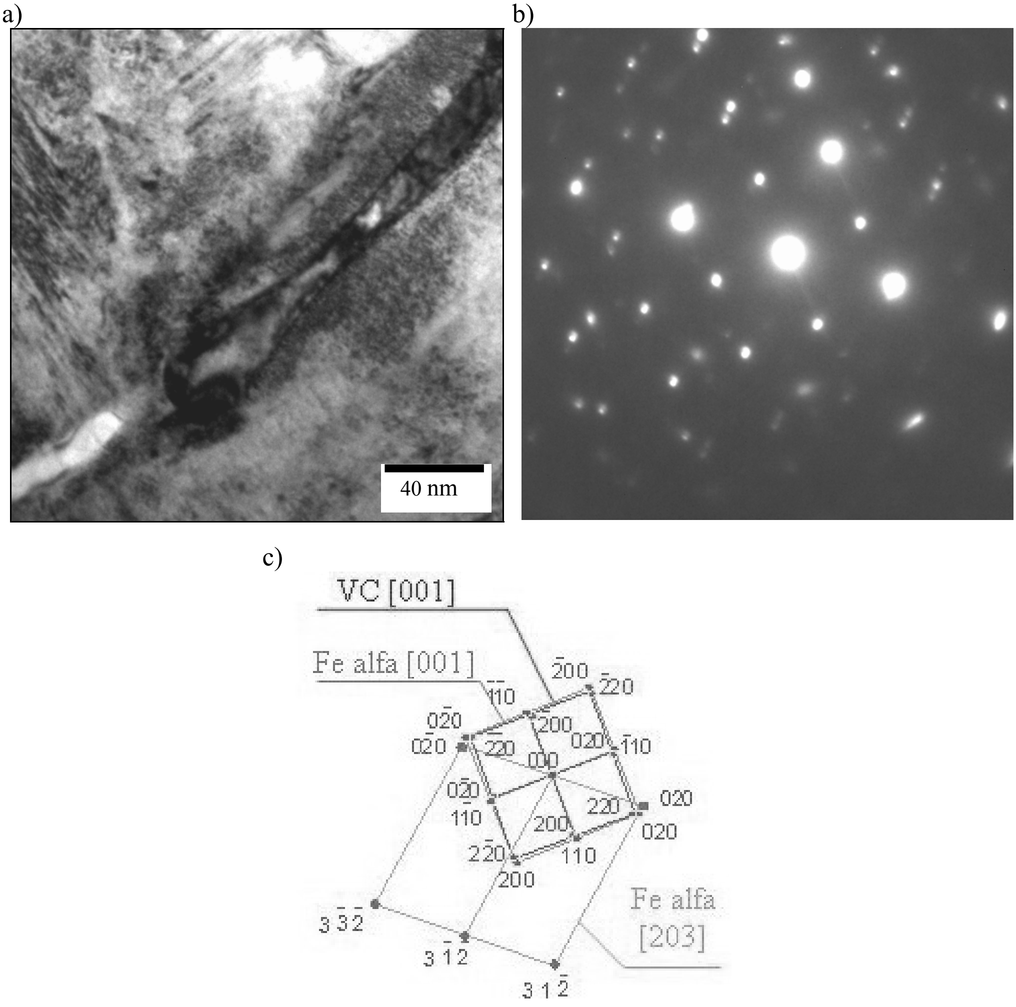


Figure 24. *Structure of thin foil made of the 32CrMoV12-28 steel after alloying with VC vanadium carbide, laser beam power of 1.6 kW, a) image in bright field, b) diffraction pattern from the area as in figure a), c) diffraction pattern solution for figure b)*

The selected mechanical and functional properties of hot-work tool steel subjected to laser remelting and alloying were also examined in the course of the materials science research. Their hardness, microhardness, roughness, wear resistance and thermal fatigue strength was examined in particular [52]. Laser treatment in the majority of cases improves the hardness of

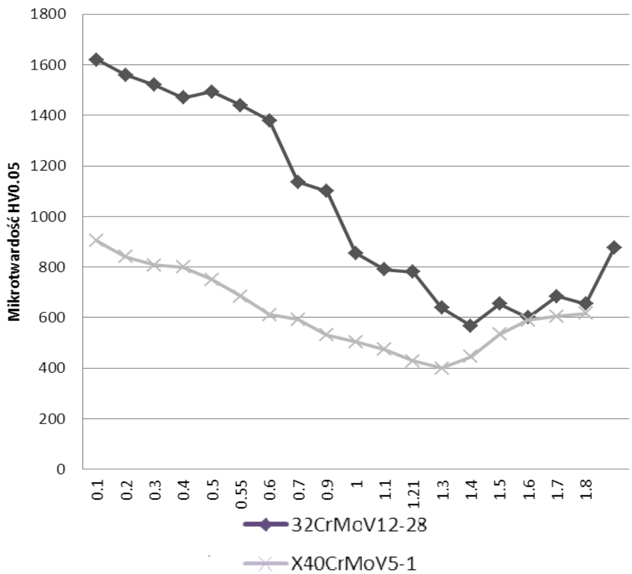


Figure 25. *Variations to the surface layer microhardness of the X40CrMoV5-1 and 32CrMoV12-28 hot-work alloy tool steels alloyed with laser using the TaC tantalum carbide; laser power of 1.6 kW*

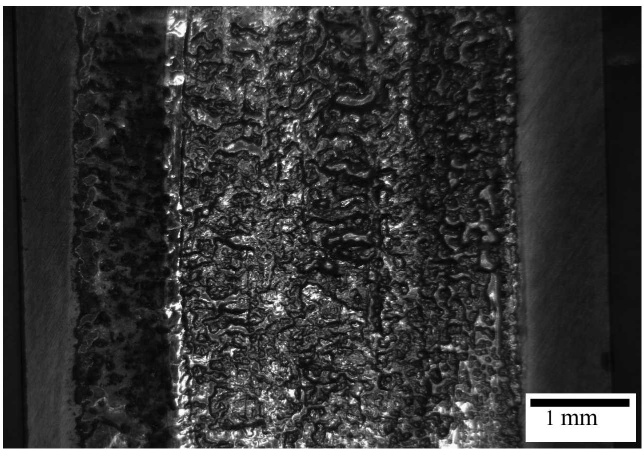


Figure 26. *Wear trace of the surface layer after an abrasion test acc. to ASTM G65 for the X40CrMoV5-1 steel alloyed with the WC tungsten carbide powder, laser power of 1.2 kW*

the investigated steels. The hardness of the surface layer alloyed with carbide powders is growing along with the higher power of laser used for alloying [53, 54]. The results of microhardness measurements at the lateral section of the surface layer according to distance from the surface of samples indicate that microhardness is growing in the majority of cases of laser remelting and/or alloying using carbide powders. An area was also identified in all the microhardness measurements of the surface layer of the heat treated, remelted and/or laser-alloyed steel where hardness is clearly decreasing. Such area is present along the whole width of the heat-affected zone limit and native material [55]. Such lower hardness is seen as a consequence of steel tempering during laser treatment when steel is heated to a temperature higher than the tempering temperature [56] (Fig. 25). The tribological properties of steel are rising along with the growing surface layer hardness after laser alloying. Figs. 26 and 27 illustrate the

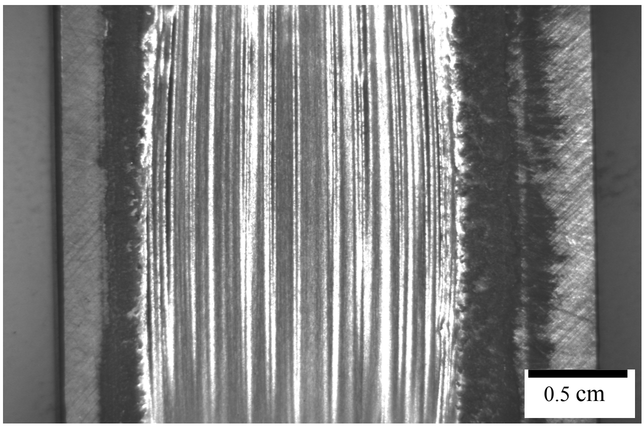


Figure 27. *Wear trace of the surface layer after an abrasion test acc. to ASTM G65 for the 32CrMoV12-28 steel alloyed with the TiC titanium carbide powder, laser power of 2.0 kW*

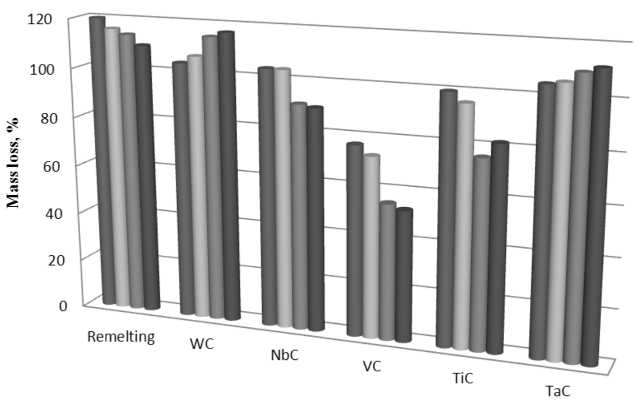


Figure 28. *A relative loss of mass measured when testing the wear resistance of the 32CrMoV12-28 steel remelted and alloyed by laser with carbide powders within the laser power range of, respectively: 1.2, 1.6, 2.0 and 2.3 kW*

wear traces of the surface layers of tool steels, respectively the X40CrMoV5-1 and the 32CrMoV12-28, after testing abrasibility acc. to ASTM G65. Wear resistance was also tested for the steels subjected to remelting and alloying with carbide powders [57-59]. Figs. 28 and 29 show a relative loss of mass measured when testing the wear resistance of X40CrMoV5-1 steel. The detailed research results for the mechanical and functional properties made for the X40CrMoV5-1 and the 32CrMoV12-28 steel remelted and alloyed with different carbide powders using laser with different power is listed in Table 8.

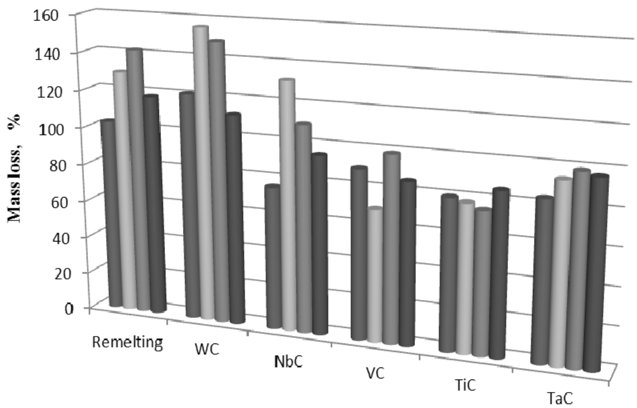


Figure 29. *A relative loss of mass measured when testing the wear resistance of the X40CrMoV5-1 steel remelted and alloyed by laser with carbide powders within the laser power range of, respectively: 1.2, 1.6, 2.0 and 2.3 kW*

Table 8. *Research results of mechanical and functional properties of hot–work alloy tool steels remelted and alloyed using HPDL*

Substrate material	Laser power of, kW	Surface layer remelting depth, mm	Roughness R_a, µm	Hardness HRC	Microhardness expressed in universal scale of relative states	Wear resistance *) (relative mass loss of sample), %	Thermal fatigue strength / Average depth of cracks, µm
(K) The laser remelting of hot-work alloy tool steels (without powders)							
X40CrMoV5-1	1.2	0.56	1.26	54.51	6	64	42
	1.6	1.03	1.52	56.00	3	78	39
	2.0	1.47	2.55	56.76	5	85	32
	2.3	1.67	3.57	57.71	6	70	28
32CrMoV12-28	1.2	0.52	0.58	53.20	1	120	76
	1.6	0.92	0.60	51.50	1	116	74
	2.0	1.13	0.67	44.63	2	114	63
	2.3	1.67	0.82	41.10	2	110	6

Substrate material	Laser power of, kW	Surface layer remelting depth, mm	Roughness R_a, μm	Hardness HRC	Microhardness expressed in universal scale of relative states	Wear resistance *) (relative mass loss of sample), %	Thermal fatigue strength / Average depth of cracks, μm
(L)	The laser alloying of the NbC niobium carbide powders in the surface of hot-work alloy tool steels						
X40CrMoV 5-1	1.2	1.43	12.13	58.37	8	72	no data available
	1.6	1.90	14.82	55.70	7	78	no data available
	2.0	2.64	23.18	56.64	9	67	no data available
	2.3	3.32	25.90	58.37	10	71	no data available
32CrMoV1 2-28	1.2	1.28	6.40	55.20	6	104	67
	1.6	1.74	9.80	56.10	7	104	54
	2.0	2.45	11.20	60.73	8	91	62
	2.3	2.61	18.20	60.66	9	90	51
(M)	The laser alloying of the TaC niobium carbide powders in the surface of hot-work alloy tool steels						
X40CrMoV 5-1	1.2	1.62	4.94	56.71	6	52.5	24
	1.6	2.33	5.40	58.82	8	56	25
	2.0	3.00	5.64	58.39	8	61	19
	2.3	3.52	8.66	60.26	9	55	18
32CrMoV1 2-28	1.2	0.99	6.80	65.06	9	105	no data available
	1.6	1.87	9.40	65.46	10	106	no data available
	2.0	2.56	9.30	67.26	10	110	no data available
	2.3	2.79	14.40	67.13	10	112	no data available
(N)	The laser alloying of the TiC niobium carbide powders in the surface of hot-work alloy tool steels						
X40CrMoV 5-1	1.2	1.42	2.46	55.34	10	49	24
	1.6	1.66	5.34	56.53	8	47	24
	2.0	2.21	6.14	57.55	8	46	20
	2.3	2.56	8.40	62.09	9	52	16
32CrMoV1 2-28	1.2	0.85	7.80	53.20	1	100	18
	1.6	1.39	11.10	51.50	1	96	15
	2.0	1.78	12.70	44.63	2	76	1
	2.3	2.13	12.90	41.10	2	82	8
(O)	The laser alloying of the VC niobium carbide powders in the surface of hot-work alloy tool steels						
X40CrMoV 5-1	1.2	1.32	9.20	55.68	8	53	24
	1.6	1.62	9.60	61.78	7	45	24
	2.0	2.18	9.80	62.57	7	58	23
	2.3	2.40	10.82	62.56	8	50	22
32CrMoV1 2-28	1.2	1.30	9.60	57.16	5	77	16
	1.6	1.55	10.60	56.66	5	73	14
	2.0	1.93	11.60	57.30	5	55	7
	2.3	2.27	19.20	58.36	6	53	4
(P)	The laser alloying of the WC niobium carbide powders in the surface of hot-work alloy tool steels						
X40CrMoV 5-1	1.2	1.46	18.62	55.62	5	76	61
	1.6	1.79	20.38	57.53	1	94	50
	2.0	1.98	23.82	57.93	1	94	46
	2.3	2.12	36.74	58.66	5	67	47
32CrMoV1 2-28	1.2	0.81	26.80	53.20	5	104	no data available
	1.6	1.27	30.40	51.50	5	107	no data available
	2.0	1.39	33.70	44.63	6	115	no data available
	2.3	1.91	33.80	41.10	6	117	no data available
*) 100% mass loss of sample has been assumed for the 32CrMoV12-28 steel laser treated with TiC within the laser power range of 1.2 kW.							

The remelted zone (RZ) and the heat-affected zone (HAZ) can be distinguished between in the surface layer as a result of the remelting of the tested steels with their thickness depending on the laser power used for remelting. If steel remelting is carried out without inserting alloying additives such as carbide powders into the liquid metal pool, then a small increase in the properties of the surface layers of the steels examined is seen as compared to their respective properties obtained in conventional heat treatment, depending on the power of the laser beam used for remelting [60]. Likewise, the surface roughness of the steels alloyed with carbide powders is growing as the power of the laser beam increases within the entire range. This is caused by the presence of strong convective currents in liquid steel induced by the high power of the laser beam and fast crystallisation connected with the impact of a stream of shielding gas [61]. If the low laser beam power rating is applied, the remelting structure is relatively homogenous with its bottom being flat. The waving of the remelting bottom increases along with high higher laser beam power. The hardness of the surface layer of the steel examined achieved as a result of remelting is growing insignificantly as compared to the hardness of steel achieved after conventional heat treatment [62]. Along with an insignificant improvement of the surface layer hardness of the steels examined as a result of remelting, wear resistance is improving insignificantly as compared to the surface layers formed after alloying with carbide powders. Thermal fatigue strength for the steels subjected to remelting only is slightly higher than the strength achieved after standard heat treatment [63]. During laser alloying with powders containing WC, NbC, VC, TiC or TaC, they can be partially dissolved in a liquid metal pool or the carbides remain unsolved thus forming conglomerates as the unsolved grains of carbide powder are melted into the melted metal substrate. Abrasive wear resistance grows compared to steel resistance following standard heat treatment. An improvement in tribological properties is related to an improvement in steel hardness which, in turn, is caused by the structure being refined [64-66]. Thermal fatigue strength in case of alloying with carbide powders is also growing versus the resistance of the surface layers of the steels treated conventionally [56, 67, 68]. The correctly selected conditions of alloying such as laser power and scanning rate permit to achieve the high quality of surface layers free of cracks and featuring a regular, flat shape of the remelting face. The carbon phases of the powders used for alloying are present in the surface layer structure of the steel subjected to laser alloying, including: the WC tungsten carbide, the VC vanadium carbide, the NbC niobium carbide, the TaC tantalum carbide and the TiC titanium carbide. The investigations performed have evidenced that the surface layers produced in the laser remelting and/or alloying using carbide powders of the X40CrMoV5-1 and the 32CrMoV12-28 steel using a high power diode laser (HPDL) are characterised by higher mechanical and functional properties as compared to steels undergoing conventional heat treatment.

6.3. Strategic development directions of surface laser treatment of hot-work steels

A strategic position of the relevant, specific technologies of the laser remelting and alloying of alloy hot-work tool steels with carbide powders was identified by means of the matrix of strategies for technologies. A dendrological matrix of technology values was developed to determine the value of the relevant, specific technologies analysed. The matrix considers technology potential and attractiveness. The evaluation of positive and negative environment influence on the relevant, specific technologies was visualised with a meteorological matrix of environment influence [13]. The results obtained were entered into the matrix of strategies for technologies (Fig. 30) using software. As regards the N technology (8.79, 7.86) of laser treatment of hot-work tool alloy steels using the TiC titanium carbide powder and the O technology (8.61, 7.80) corresponding to the use of vanadium carbide VC powder, it is recommended to apply the oak in spring strategy. The strategy consists in developing, strengthening and implementing an attractive technology with a high potential in the industrial practise in order to achieve a spectacular success. The oak in summer strategy should be employed for the technology L (8.13, 6.15) of laser treatment of hot-work alloy tool steels using the NbC niobium carbide powder and for the technology M (8.22, 6.44) corresponding to the use of the TaC tantalum carbide powder. The strategy provides for that the attractiveness and potential of the technology shall be used in a risky environment and the difficulties that may arise will be avoided while matching a product to the customer demands preceded with thorough marketing research. The oak in autumn strategy needs to be implemented for the laser treatment of steel hot-work alloy tool steels using the WC tungsten carbide powder marked with the symbol P (8.40, 3.63). Such way of acting is connected with achieving successes with an attractive, stable technology at the predictable market and is combined with seeking new markets, customer groups and the products than can be produced with the technology. As far as the (K) laser remelting of hot-work alloy tool steels is concerned, it is recommended to use the dwarf mountain pine in summer strategy that recommends that a technology with a high potential should be made more attractive and modernised and to conduct marketing research and customise a final product to the customer's demands.

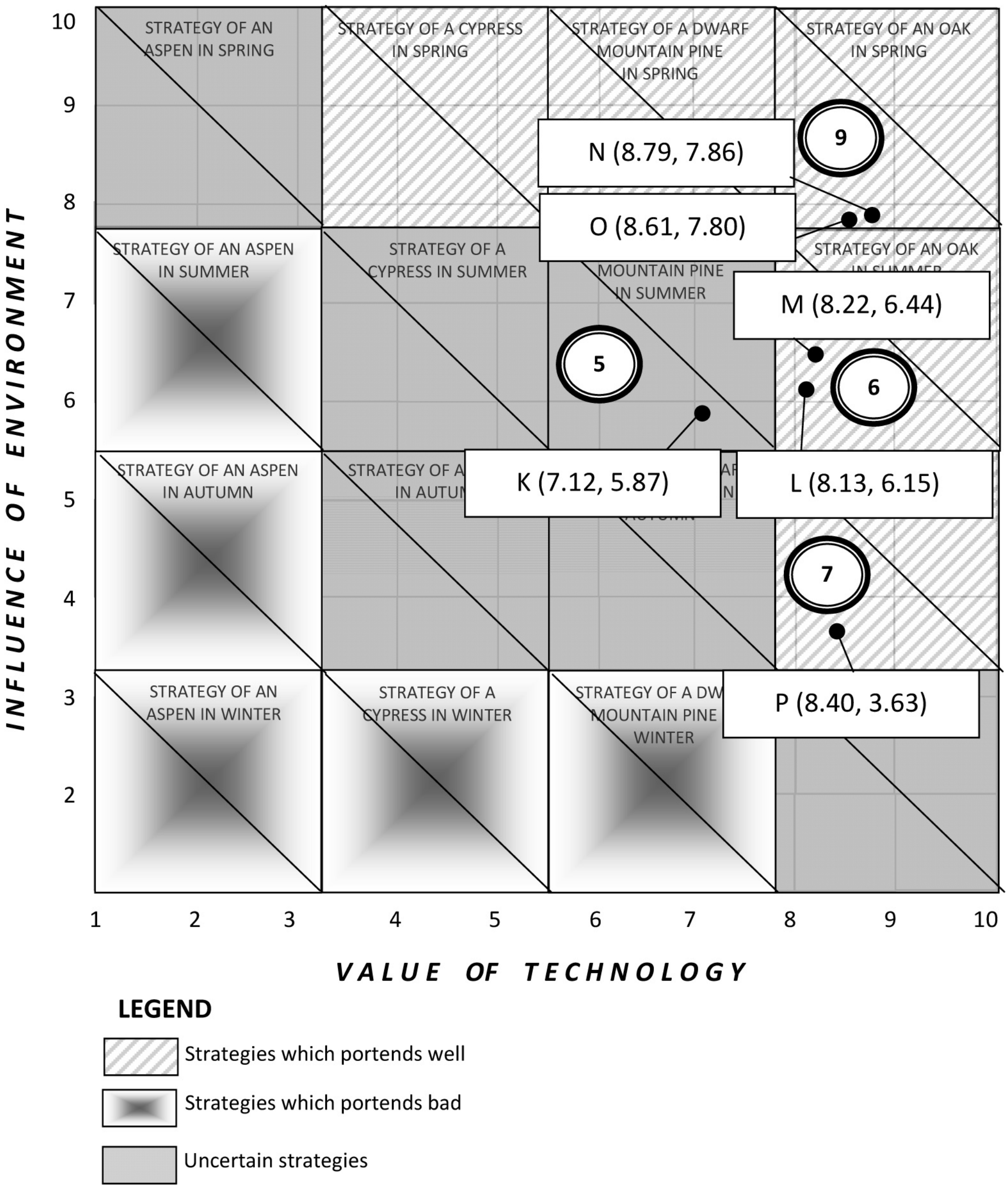
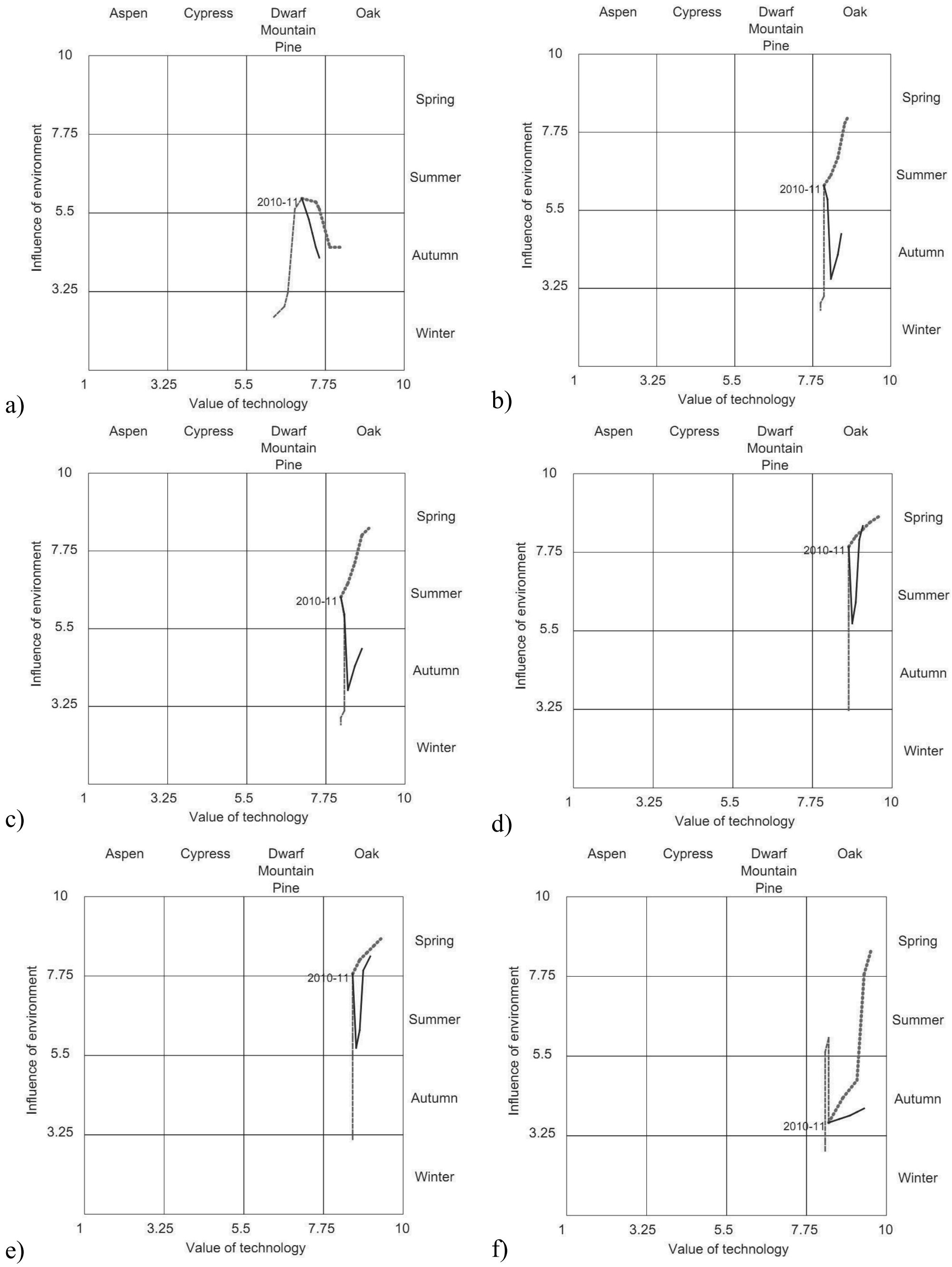


Figure 30. *The matrix of strategies for technology prepared for (K) laser remelting and alloying of hot-work alloy tool steels using NbC (L), TaC (M), TiC (N), VC (O) and WC (P) powders*



Types of strategic development tracks:
•••••• Optimistic ▬▬ Neutral ▬ ▬ Pessimistic

Figure 31. *Strategic development tracks prepared for (a) laser remelting and alloying of hot-work alloy tool steels using as follows: (b) NbC, (c) TaC, (d) TiC, (e) VC and (f) WC powders*

Strategic development tracks for the individual specific technologies representing a forecast of their development for the years of: 2015, 2020, 2025 and 2030 according to the three variants: optimistic, pessimistic and the most probable one, were next entered into the matrix of strategies for technologies. Simplified charts presenting the results of all the investigations carried out for the six analysed groups of technologies corresponding to the different types of powders deposited or to remelting without using powders are given in Figs. 31a-f. technology roadmaps and technology information sheets being a useful tool of comparative analysis according to the materials science, technological or economic criterion adopted were prepared at the last stage of the works using reference data in form of the results of materials science and foresight research and this is discussed in detail in the chapter 6.

7. Summary

The scenario method was employed in order to identify the forecast development directions of materials surface engineering. As there is no one correct and generally accepted method of creating the scenarios of future events or a management algorithm recommended for implementation in the scenario creation process, it became necessary to elaborate a custom concept that would aptly merge a presentation and description of the phenomena featuring a different extent of generality and seize the cause and effect relationships existing between them. In order to solve the so formulated research task, all the phenomena analysed were split into the three groups: a macrogroup with the single critical phenomena of the general nature characterised by strong interaction with the other phenomena; a mesogroup with a limited number of phenomena interacting moderately with the other phenomena and a microgroup comprising numerous specific phenomena highly sensitive to the interaction of other phenomena. Deductive reasoning by way of a synthesis was undertaken under the research consisting in seeking the combinations of micro- and mesofactors that would contribute, with a specific probability, to the occurrence of each of the three possible macroscenarios in the future. A simple method of presenting the research results is used in the chapter. The investigated phenomena are, therefore, presented starting with the highest level of generality (macro), through an indirect level (meso) ending with the most detailed aspects (micro). A cross analysis of how the key mesofactors of materials surface engineering development and the individual thematic areas are impacting the emergence of each of the three alternative macroscenarios, i.e. optimistic, neutral and pessimistic scenario, was undertaken using artificial neural networks. Due to the scale of the phenomena described, a representative group of laser technologies in surface engineering was chosen to demonstrate the method of presenting the development directions of the phenomena for the mesolevel, and laser remelting and alloying with special stress focus on hot-work alloy tool steels was chosen for the microlevel. A development forecast of laser technologies in materials surface engineering was established based on the results of the e-Delphix method differing from the classical Delphi method in that experts are surveyed electronically and in that the level of generality for the questions asked to the experts is growing along with the subsequent iterations of the research. The results of the foresight research are provided graphically in a bar chart. In order to identify the strategic position of the relevant groups of the critical laser surface treatment technologies against the thematic area of "Laser technologies in surface engineering", each of the groups was placed into a matrix of strategies for technologies. In addition, a chart was prepared presenting, in percents, the values of the predicted growth, stabilisation and decrease in the importance of the individual critical technologies as projected by the experts. The results of the materials science-foresight research concerning laser remelting and cladding of hot-work alloy tool steels with special emphasis laid on the results of materials science investigations and the strategic position of the specific analysed technologies was presented in the matrix of strategies for technologies. The forecast strategic development tracks of the relevant, specific technologies were next entered into the matrix. Technology roadmaps and information sheets were also prepared for the groups of the critical technologies and specific technologies.

The approach discussed allows to present the development directions of materials surface engineering according to the level of generality and according to the influence intensity of the phenomena analysed on other phenomena. A hybrid was created to fulfil this task. The hybrid embraces a collection of analytical methods and tools including: the scenario method, artificial neural networks, e-Dephix method, statistical lists as bar charts, foresight matrices together with technology development tracks, technology roadmaps and technology information sheets. Moreover, the results of the classical materials science methods are taken into account at the microlevel.

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