FAULT TREE ANALYSIS FOR BRINELL HARDNESS MEASUREMENT

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ABSTRACT

Purpose: The purpose of the paper is to determine the probability of the top event (top outcome) for Brinell hardness measurement. Top event in this case is defined as the failure of the measurement process. If the top event occurs, the measurement cannot be realized, or if the indentation (measurement) is realized, it cannot be calculated because of the gross error. The probability of the top event was evaluated by the quantitative Fault tree Analysis (FTA) with the direct numerical calculation and Monte Carlo simulation. While applying the Brinell method, the surface of the material is subjected to a standard pressure for a standard defined length of time by means of a carbide ball with a defined diameter. The diameter of the resulting indentation is inversely proportional with the hardness.

Methodology: Used methodology is documented in the standard STN IEC 61 025:2007 Fault tree analysis (FTA). The Ishikawa income – outcome diagram was used to build Fault Tree Analysis. Statistical data of elementary failures (representing incomes) were collected during one year, and we also used data from a longer period (if available), especially for rarely occurring elementary failures. The elementary failures produce top event (representing outcome). With the knowledge of the probability of elementary failure or its intensity, we can estimate the probability of the top event. After creating the fault tree analysis, the excel program was developed in order to use the fault tree analysis to calculate the probability of the top event. Program allows accelerate basic calculation, as well as comfortable substitution the values of probability of occurrence individual basic events in order to study their influence on the top event. A Monte Carlo simulation was used as the verifying calculation. It is a numerical calculation method, which is based on the use of random variables and the theory of probability. The verification was carried out using Quantum XL software.
Findings: As for the findings, the probability of the top event is disproportionately high (0.257). It means the failure every fourth measurement. Mostly it was caused by the basic events, which bind to the parts of the tester and its calibration (0.234). This problem can be solved by focusing on the service of the hardness tester or by using a better quality etalon with low uncertainty of the hardness standard value. Because of the low resolution of the balls it is necessary to prevent the unauthorized using of been non-standardized steel balls, preferably by their disposal.

Research limitation: Application of the results is limited to the hardness tester with direct measurement of the indentation dimensions, without using a computer image processing. It is likely that because of the widespread use of the hardness tester, this research will have a wide practical use at least in Slovakia and will serve to improve the quality of hardness measurement process.

Keywords: hardness; Brinell method; FTA; quality; Monte Carlo simulation

1 INTRODUCTION

The purpose of the paper is to determine the probability of the top event (top outcome) for Brinell hardness measurement.

Top event in this case is defined as the failure of the measurement process. If the top event occurs, the measurement cannot be realized, or the realized indentation cannot be measured, or it is measured but calculated value of the hardness cannot be used because it is affected by the gross error.

Method of Fault Tree Analysis (FTA) is a qualitative – quantitative analysis of the failure of the system in the form of the fault tree to determine as defined top event causing, may potential causing or contribute to the occurrence elementary failures of lower-lying elements or external influences. It is a method that directly focuses on the modes of failures. FTA is a graphical representation of the major faults or critical failures associated with a product and the causes for the faults and potential countermeasures (International electrotechnical commision, 2007).

It uses logical symbols: gate AND (the output event occurs only if all of the input events occur)

\[ P(G) = \prod_{i=1}^{n} P(A_i) \]  \hspace{1cm} (1)

and gate OR (the output event occurs only if any of the input events occur)

\[ P(G) = 1 - \prod_{i=1}^{n} (1 - P(A_i)) \]  \hspace{1cm} (2)
A is probability of the failure. The probability or the intensity of the incidence of the top event can be estimated from the probability of occurrence or the intensity of incidence of basic events.

FTA method is defined in the standard BS 61025: 2007 (International Electrotechnical Commission, 2007).

The fault tree is displayed in a form that can be understood, analyzed and modified as necessary to facilitate the identification of fault monitoring. Based on the top-level of the fault tree - top event, which corresponds to an undesirable state, we can move down the levels of the fault tree to the basic event on the appropriate level of fault tree analysis. In this way, it is possible to investigate any dependence on the system and its subsystems. This method of the analysis requires a systematic approach, which is necessary to capture the functional links between the elements of the observed system. The method easily allows to discern the causal dependence of the top event passing from the top down the tree.

FTA is particularly suitable for the analysis of complex systems, which consist of functionally bonded or dependent subsystems. The method has found its place wherever it was necessary to deal with complex systems and seek, reduce the failure, or improve the quality, namely in sectors such as energy, space, aviation, nuclear energy, chemical processes, complex information systems and more (Rajkumar, 2011).

FTA method was first used in 1962 by Bell Telephone Laboratories in the development of intercontinental ballistic missiles (Minuteman Intercontinental Ballistic Missile Launch Control System) and was improved by Boeing in 1966. It started to use in the nuclear power industry since 1975. Its use in this industry experienced a significant increase after an accident in Three Mile Island in 1979. It is an important part of the reliability engineering.

When Fault Tree Analysis proceed step by step, the specific sequence of steps is not unified for all systems. The below sequence of steps is the minimum that must be included each analysis:

1) Defining the analyzed systems, purpose and scope of the analysis and the basic assumptions that have been taken,
2) Defining of the fault,
3) Construction of the fault tree (in vertical or horizontal format),
4) Qualitative or quantitative analysis of the fault tree.

The aim of qualitative or logical analysis is to find all reasonably possible combinations of factors operating conditions, environmental conditions, human errors and failures of elements of which could lead to the top event.
A manual solution in qualitative analysis of the fault tree is currently done only in the case of simple trees (usually a few tens of basic events), otherwise use special software products.

Quantitative or numerical analysis of the fault tree can be made if probabilistic data of basic events are known. The aim of this analysis, used in the presented paper is to provide a quantitative of the probability of occurrence of the top event or a selected set of events. The probability that the top event occurs in a specified interval (1 year) of system operation was determined (Plura, 2001; Clemens, 2002; Vesely, 2002; Nouri, 2014).

2 ANALYZED SYSTEM OF THE HARDNESS MEASUREMENT

The Brinell macro-hardness test is the standard method for measuring the hardness of metals: the surface is subjected to a standard pressure for a standard length of time by means of a tungsten carbide ball with defined diameter. The diameter of the resulting indentation is measured under a microscope and is inversely proportional to the hardness. Among used hardness tests, the Brinell ball makes the deepest and widest indentation. The test averages the hardness over a wider amount of material, which will more accurately account for multiple grain structures, and any irregularities in the uniformity of the alloy (typical for cast structure) and soft materials. A wide indentations, on the other hand, can impair the surface of the test items.

The method define (at least) two technical standards (International Standards Office, 2005). The calibration of the tester is required before the measurement. The indirect calibration using the standard in form of the standard reference block with defined specified hardness and its uncertainty is used as a routine method. The values of repeatability $r_{rel}$, a maximum error of tester $E_{rel}$ and relative expanded uncertainty $U_{rel}$ shall not exceed the values permitted the standard. The standards define the temperature interval for calibration and the actual measurement of hardness.

3 ISHIKAWA DIAGRAM

An Ishikawa or fishbone diagram, also called cause and effect diagram, is a visualization tool for categorizing the potential causes of the problem – the top event in order to identify its root causes. The design of the diagram looks much like a skeleton of a fish. Fishbone diagrams are typically worked right to left, with each large “bone” - “ribs” of the fish branching out to include smaller bones containing more detail. The head and backbone of the fish list the top event – the problem or issue to be studied. Four “causes” that contribute to the problem (environment, source of electrical power, a construction element of the
tester and quality of the test item) create the first bones (ribs) of the fish. Other, more specific levels of bones (horizontal, vertical, horizontal ...) can be added to the “ribs” until the cause of the problem can be divided into subcategories. The practical number of levels is usually 4 to 5. The lowest level is a basic event. When the diagram is complete, we provide an overview of the possible causes (not symptoms) of the solved problem. It is important to explore more times repeating subcategories to find a link between them, or eliminate unnecessary duplication (in triplicate). Correctly designed diagram significantly facilitate the design of fault tree analysis. The diagram of analyzed process is in Figure 1.

Figure 1 – Ishikawa diagram of analyzed process
4 INPUT DATA

Statistic data of basic events were collected during one year, or (if available); data for a longer period were also used, especially for rarely occurring basic events. They were used in the form of probability (in decimals) of their occurrence in quantitative calculations. Universal hardness tester HPO 250 working in the Brinell mode made in 1982 in the former GDR was placed in the laboratory, which is part of the hall (the room in the room). The hall is tempered; the laboratory is equipped with a radiator of central heating, the ventilation of the laboratory is possible only to the hall. Unfortunately, in the laboratory experimental device is placed – electric furnace. Its use results in the increase of the temperature in the laboratory. The hardness tester and the furnace were infrequently used, as appropriate, the tester by several operators. The indirect calibration of the tester was applied before each measurement. Only materials based on iron (structural steel) were measured. It was, therefore, possible to carry out all measurements with the same load (1839 N) and the diameter of the
ball (2.5 mm). Equally for all calibration the same standard with defined specified hardness \(H_c = 242.2 \text{ HBW 2.5} / 187.5\) was used.

5 THE DESIGN AND QUANTITATIVE ANALYSIS OF THE FAULT TREE BY DIRECT CALCULATION

The FTA diagram (Figure 2) was designed using Ishikawa diagram (Figure 1). The branch G1 represents the influence of the environment. It is developed to the basic events: K – the exterior temperature is above 30°C, L – the furnace is on, M – the exterior temperature is under 0°C, Z – the fault of the central heating of the laboratory and Ž – the shutdown of heating during the holidays. The probability of failure of individual sources is given in Table 1.

Table 1 – The description of the basic events

<table>
<thead>
<tr>
<th>Code</th>
<th>Probability of failure</th>
</tr>
</thead>
<tbody>
<tr>
<td>K</td>
<td>0.273970</td>
</tr>
<tr>
<td>L</td>
<td>0.013699</td>
</tr>
<tr>
<td>M</td>
<td>0.041096</td>
</tr>
<tr>
<td>Z</td>
<td>0.054790</td>
</tr>
<tr>
<td>Ž</td>
<td>0.027397</td>
</tr>
<tr>
<td>B</td>
<td>0.000026</td>
</tr>
<tr>
<td>C</td>
<td>0.000013</td>
</tr>
<tr>
<td>O</td>
<td>0.001200</td>
</tr>
<tr>
<td>D</td>
<td>0.000400</td>
</tr>
<tr>
<td>P</td>
<td>0.000100</td>
</tr>
<tr>
<td>Q</td>
<td>0.000100</td>
</tr>
<tr>
<td>R</td>
<td>0.000267</td>
</tr>
<tr>
<td>S</td>
<td>0.000400</td>
</tr>
<tr>
<td>G</td>
<td>0.000400</td>
</tr>
<tr>
<td>H</td>
<td>0.001200</td>
</tr>
<tr>
<td>CH</td>
<td>0.100000</td>
</tr>
<tr>
<td>T</td>
<td>0.010000</td>
</tr>
<tr>
<td>U</td>
<td>0.010000</td>
</tr>
<tr>
<td>W</td>
<td>0.010000</td>
</tr>
<tr>
<td>J</td>
<td>0.010000</td>
</tr>
</tbody>
</table>

The branch G2 represents possible faults of the source of electrical power. It is developed to the basic events: A – the plug is without power (total blackout), B – the fault of the plug and C – the fault of the power supply cable or it of the electrical system of the tester.

The branch G3 represents possible faults of the construction elements (mechanical and optical) and faults due to non-compliance with the requirements of the standard for calibration. It is developed to the basic events: N – the tester is not vertical (in the water – level), the result is jammed load, O – the load controlling device failed, D – missing ball, operator forgot to insert it, P – the operator selected the diameter of the ball incorrectly, Q – the material of the ball is unsuitable, i.e. the steel instead of tungsten carbide, E – insufficiently
tightened sleeve of the ball holder, F – incorrect position of the support of the test item, R – burnt out bulb, S – broken contact of the bulb, G – the fault of the lever to release the applied load, H – the fault of exchange optics/ball systems, CH – the limit position of the micrometric screw of the indentations measuring device was exceeded, I – chosen objective does not provide appropriate magnification, the tester does not meet the requirements: T – for repeatability, U – for maximum error and V – for relative expanded uncertainty at calibration.

The branch G4 represents possible faults of the quality of the test item. It is developed to the basic events: W – scratched surface, X – the surface of the test item is affected by corroding process, Y – greasy surface and J – unwanted confusion of the test items.

The probability of the failure is 0.0003815 in the branch G1, 0.000052 in G2, 0.23367 in G3 and 0.030671 in G4. The probability of the top event G0 is 0.257497. About ¼ of measurements is, therefore, unsuccessful, which is unacceptable. The branch with basic events E, F, CH, I, T and V, is critical. For these events, it is necessary to focus on the corrective action. It is necessary for the operator to check the position of the support of the item (F) before each measurement. The shakes of tester in the measurement can result in unacceptable rotation of the support. It is rotatable and to secure its position, affecting the result of measurement is not possible. It should also be securely tightened sleeve of the ball holder (E) and its permanent control. Unqualified operator can forcibly exceed the fixing limit position of the micrometer screw (CH). This fact will cause damage of the device. The corrective action is difficult to achieve in this case. Experienced operators and using of better quality standard (with lower uncertainty) can improve the calibration parameters (T, U, V). If these corrective actions reduce the probability of the failure to 0.1 in branch G3, the probability of the top event (G0) will 0.127982 assuming constant values of probabilities in other branches (Sokoliová, 2014).

5 EXPLOITATION OF MONTE CARLO METHOD IN EVALUATION OF THE FAULT TREE

The Monte Carlo method or probability simulation is a means of statistical evaluation of mathematical functions using random samples. In the Monte Carlo simulation, a random value is selected for each of the tasks.

It is a technique used to understand the impact of risk and uncertainty in forecasting models. When you have a range of values as a result, you are beginning to understand the risk and uncertainty in the model. The key feature of a Monte Carlo simulation is that it can tell you – based on how you create the ranges of estimates – how likely the resulting outcomes are. The model is calculated based on this random value. The result of the model is recorded, and
the process is repeated. A typical Monte Carlo simulation calculates the model hundreds or thousands of times, each time using different randomly-selected values. When the simulation is complete, we have a large number of results from the model, each based on random input values. These results are used to describe the likelihood, or probability, of reaching various results in the model. The example of such results can be the calculation of hardness measurement uncertainty, which is carried out in the laboratories for testing metallic and non-metallic materials. The laboratories are accredited according to EN ISO / IEC 17025: 1999. The numerical results are confirmed and formed by using the method of Monte Carlo simulations (MCS) (Sienkowski, 2013; Raychaudhuri, 2008; Kuselman, 2014; Barsic, 2006).

The simulation determined the probability (in %) that will fulfill the requirement of maximum probability 0.1 of branch G3. The input values were basic events E,
F, CH, T, U and V with probability between 0 and the value given in Table 1. Triangular distribution was considered for all inputs. The probability given in Table 1 was considered for other basic events as a constant value. Software QUANTUM XL was used. The graphical outputs for 1000 simulations are in Figure 3. The conformity with the requirement was then only 1.1%. If input values were probabilities between 0 and ½ of table values, the conformity of the output will be 84.1%, Figure 4.

6 CONCLUSIONS

As for the findings, the probability of the top event is disproportionately high (0.257). It means the failure every fourth measurement. Mostly it was caused by the basic events, which bind to the parts of the tester and its calibration (0.234). This problem can be solved by focusing on the service of the hardness tester or by using a better quality etalon with low uncertainty of the hardness standard value. Because of the low resolution of the balls it is necessary to prevent the unauthorized using of been non-standardized steel balls, preferably by their disposal.

Application of the results is limited to the hardness tester with direct measurement of the indentation dimensions, without using a computer image processing. It is likely that because of the widespread use of the hardness tester, this research will have a wide practical use at least in Slovakia and will serve to improve the quality of hardness measurement process.

Application of Monte Carlo method for FTA provides fast calculation of the probability of the top event, taking into account not only the probability of basic events, but also intervals of their possible occurrence and also their distribution. This calculation introduces a dynamic element that models the behavior of the analyzed system more realistic than commonly used static model. This fact the most significant contribution to the existing body of knowledge. If there is an appropriate software input conditions can vary widely, and determine the optimum arrangement of the system is not time-consuming.

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