COST-ORIENTED FMEA OF HOT ROLLED WIRE PRODUCTION

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Abstract

One of essential activities in quality planning is the review of the designed product and of its realization process. Its objective is to optimize their capability to meet the defined customer requirements. For this purpose, the FMEA method (Failure Mode and Effect Analysis) is used. The method consists in the following: a team analysis of potential occurrence of failure modes in the design in question, assessment of their risks and preparation and implementation of preventive measures for improving the quality of the product design and of the process. Today’s approach to FMEA lacks the quantification of costs of potential occurrence of specified failure modes and costs of their analysis. Yet, this criterion may be of key importance for strategic decisions on either accepting or rejecting proposed preventive measures. This paper describes the methodology of a cost-oriented FMEA process, which takes into account the economic aspects of potential failure modes for the product. It also presents a practical application of FMEA in manufacturing drawn steel spring wire.

Keywords: process FMEA, cost-oriented FMEA, wire rolling, rolled wire defects

1. INTRODUCTION TO THE PROBLEM

Quality of products and services offered is one of critical success factors for any organization attempting to succeed in today’s global market environment. If we use the definition of quality as the “degree of fulfilment of requirements by a set of inherent characteristics” [1], one can state that the level of quality of a product (service) is given by the level of customer satisfaction. The level of customer satisfaction is defined as the “aggregate of feelings of a customer resulting from differences between his expectations and perceived reality in the market” [2]. Hence, the customer satisfaction, and thus the potential success of an organization, hinges on the ability of the organization to supply customers with products which meet their requirements, needs and expectations. It is generally accepted that the customer satisfaction is substantially determined as early as the quality planning phase. This part of the product lifecycle belongs to pre-production stage. It is aimed at designing and developing the product and its realization process. Various authors suggest that about 80% of the final quality of a product is achieved at the quality planning stage [3].

The purpose of any organization should be to identify customer requirements and to design a product which meets them in full. This is why, prior to approving and releasing the final product design to production, the design should be reviewed and optimized in order to assess its capability to meet specified requirements and in order to minimize the risk of product failure modes occurring in the course of its production and use. The FMEA method is used for this purpose.

2. FAILURE MODE AND EFFECT ANALYSIS (FMEA)

FMEA method is based on the following: a team analysis of potential failure modes in the product design in question, assessment of the risks of their occurrence and preparing and implementing preventive measures for improving the quality of the product design and of the process. Experience shows that using this method may reveal up to 70 or even 90 % of potential failure modes [4]. Typical procedures used in practice are based on American automobile manufacturers’ methods QS-9000: FMEA [5] or on an almost identical methodology of the German Association of the Automotive Industry VDA 4.2 [6]. Two forms of FMEA are distinguished, depending on whether the product design or the process design are the focus: product design
FMEA (design FMEA) and process FMEA. Application of FMEA brings a number of benefits, such as [3]: reduced losses from poor quality, less changes at the realization stage, more effective utilization of resources and higher customer satisfaction. Its costs are a mere fraction of costs related to potential failure modes. FMEA is implemented at three stages: 1. Analysis and assessment of the present state; 2. Designing preventive measures; 3. Evaluation of the state after preventive measures have been implemented.

In the course of the analysis and evaluation of the present state, potential failure modes in the future product are identified which may occur during its production or service, together with their causes and consequences. This method quantifies the risks of failure modes resulting from flaws in the product or process design deficiencies. The risk levels for potential failure modes are expressed in the form of Risk Priority Numbers (RPN) obtained as a product of three criterion values: severity number, occurrence ranking and detection number. These criteria are typically assessed on a ten-point scale from 1 to 10. Preventive measures must be put in place for failure modes with too high RPN to reduce the risk of their occurrence. Tied to designing preventive measures is the definition of responsibilities and the implementation schedules. At the last stage, upon implementation of the measures, the criteria (severity, occurrence, detection) are reassessed and the RPN is calculated again. The purpose of this stage is to check the efficiency of the implemented measures. Detailed descriptions of application of FMEA method, the FMEA forms and tables for evaluation of severity, occurrence and detection numbers can be found in a number of publications [5-8].

3. COST-ORIENTED FMEA

Typical current approach to FMEA lacks the quantification of costs of potential occurrence of specified failure modes and costs of their analysis. Yet, this criterion may be of key importance for strategic decisions on accepting or rejecting the preventive measures proposed. This is why a methodology of cost-oriented FMEA process was elaborated, which takes into account the economic aspects of the product defects. The principles of application of the FMEA process according to this methodology are not substantially different from the general procedures for its application (see section 2). However, there is an important difference in calculating the RPN which, in addition to typical criteria of severity, occurrence and detection, takes into account the costs related to rectification of defects.

3.1 Calculation of Risk Priority Numbers with Cost Items

As mentioned above, the substantial difference between conventional use of FMEA and the application of the proposed methodology is the calculation of risk priority numbers. This is why this paper does not give explanation of the full methodology but only deals with the calculation of the proposed risk priority number \(RPN_C\) and the variables used. The \(RPN_C\) number is calculated as follows:

\[
RPN_C = V \cdot P_v \cdot \left( P_o \cdot C_i + P_o \cdot C_E \right)
\]

(1)

where:

- \(RPN_C\) ... risk priority number based on cost items,
- \(V\) ... severity of defect,
- \(P_v\) ... probability of occurrence,
- \(P_o\) ... probability of revealing the defect before delivery,
- \(P_s\) ... probability that the defective goods will be delivered to the customer,
- \(C_i\) ... total costs related to internal defects,
- \(C_E\) ... total costs related to external defects.

A scale from 1 to 10 [3] is used for assessing the severity and probability of occurrence of defect. The probability of a defect being revealed prior to delivery is based on evaluation of efficiency of existing inspection procedures used for assessing the process design prior to its release to production. In this case, probability estimates are used, instead of the 1 - 10 point scale. The estimates range from 0 to 1 or from 0 to 100%. (The certainty that a defect will be revealed = 1; the certainty that a defect will not be revealed and the
defective goods will be delivered to the customer = 0) [9]. The probability of the defect being delivered to the customer is the probability that the particular defect will not be revealed by existing inspection procedures and that it will reach the customer. Adding the probability of the defect being revealed prior to delivery and the probability that the defect will be delivered to the customer yields the value of 1.

Total costs related to internal defects include primarily the costs incurred in relation to internal defects. Costs related to internal defects can arise from repairable or irreparable products and include, for instance, the following:

A. Costs related to irreparable products:
   - costs of all materials, semifinished products and work expended on irreparable products,
   - costs of removal and scrapping,
   - labour costs arising from manufacturing new products (replacement for irreparable products),
   - material costs for making new products (replacement for irreparable products), etc.

B. Costs of reworking and repairing nonconforming products:
   - costs of all materials, semifinished products and work expended on irreparable products,
   - labour costs related to repair and rework of nonconforming products,
   - material costs related to repair and rework of nonconforming products, etc.

Total costs related to external defects comprise, above all, the costs paid in relation to external defects. These are the defects which were not revealed by existing inspection procedures but by the customer or in service. Such costs include, for instance: labour costs for handling complaints, costs of compensatory performance, transport costs, costs of re-packing, penalties and additional costs arising from failure to fulfil contract schedule.

Whereas the conventional risk priority number is a dimensionless quantity (in the range from 1 to 1,000), the resulting value of $RPN_C$ is expressed in currency units. The value of $RPN_C$ is key to selecting the defects and their causes, for which measures for their elimination or minimization will be prepared.

Conclusions of this paper include an example of application of cost-oriented FMEA applied according to this proposed methodology. The following section covers theoretical analysis of defects which may form in the course of wire rolling.

4. DEFECTS OF ROLLED WIRE

The quality of rolled wire (RW) has a great impact on the end-use properties and economic efficiency of production of drawn wire (DW). Technical requirements for non-patented drawn steel wires (Czech Standard class 11 steel grades) are normally lower than those laid on patented wires (Czech Standard class 12 steel grades) and the manufacturing process and equipment is simpler for class 11. Requirements for quality of rolled wire from Czech Standard class 11 steel grades are therefore lower than those for rolled wire from class 12 steel grades. We can mention the most frequent technical requirements laid on RW: largest possible mass of a single coil produced as a single piece; correct geometry, minimized dimensional deviations and out-of-roundness; lowest possible content of internal defects; appropriate chemical composition and superior chemical homogeneity across the cross-section; desirable microstructure and grain size with regard to the best possible weldability; high surface quality (minimum amount of scale, no surface defects or decarburization); uniform mechanical, physical and technological properties along the entire length of the coil.

On the other side is possible to define the most common inconsistencies on the side of suppliers: greater
variance in chemical composition of steels than the normal scope of use; surface defects (cracks, decarburized areas) content above the allowed limits stipulated in relevant technical specifications; content of internal defects (cavities, segregation) above agreed levels; insufficient degree of sorbite formation in the rolled wire (wire processed without controlled cooling); non-uniform mechanical properties along the length of the wire in a coil and variance in properties of individual heats; frequent confusion of materials; values of some parameters in individual rolled wire grades are lower than those required by foreign standards.

**Shape Defects**

The diameter of the rolled wire affects its cooling rate upon rolling and, consequently, its microstructure and mechanical properties. The ratio of the wire's surface area to its cross-section increases proportionally with decreasing diameter and the wire cools more rapidly. For this reason, thick rolled wire exhibits coarser microstructure and slightly lower strength than thin wire produced under identical process conditions. Large tolerance and large ovality of the rolled wire adversely affect mechanical properties of drawn wire, increase the consumption of drawing dies, lubricants and diminish the utilization of wire-drawing machines due to in-process wire breakages.

**Internal Defects of RW**

The wire must be free from segregations, banding, discontinuities, central shrinkage cavities or defects disrupting subsequent processing. Inclusions in iron alloys are classified into three key groups: oxides, sulphides and silicates. Properties of rolled steel wire are governed by the amount, type, plasticity, size and distribution of inclusions in the material. The amount and types of inclusions indicate the effectiveness of removal of impurities from the steel (Fig. 1 and 2). Defects occurring in production of bars include iron oxides which contaminate steel in the course of the manufacturing process. These defects are found below the surface. Fig. 3 shows iron oxide inclusion below the surface of the wire. In the course of drawing, these inclusions cause cracks to form in the wire surface (see Fig. 4).

**Surface Defects of RW**

Rods and wires, whether from steel or non-ferrous metals, are manufactured by hot rolling of continuously cast stock. Defects in the surface of the wire form in the course of these processes and also during drawing and improper handling. Surface defects and cracks in rolled wire were classified by the Japanese Iron and Steel Institute (see Fig. 5).

**Quality of Surface of RW**

*Amount and composition of scale* - affects the throughput of descaling equipment and the economic efficiency of treatment of wire surface. For these reasons, the amount of scale on the rolled wire surface should be minimized and the composition of scale should be modified to conform to requirements for various surface treatment procedures prior to drawing (pickling, blasting, bending, wire brushing and others).
Depth of surface defects - is monitored particularly in production of demanding products (hoisting cables, needles, and springs). If the surface defect depth is below 0.15 mm and its length is small, the risk of wire breakage during drawing is greatly minimized.

Decarburization of rolled wire - made from CSN class 12 steel grades significantly degrades its properties. It reduces, for instance, the fatigue strength of rope and spring wires in reverse bending and, as a consequence, the fatigue limit of springs and wire ropes. Strict requirements in relation to decarburization are laid on needle wires.

Microstructure

Microstructure of the non-patented low-carbon wire consists mostly of ferrite and small islands of pearlite along grain boundaries. Formability of this microstructure depends to greatest extent on the grain size and on presence of particles which might initiate formation of cracks (carbides, nitrides, inclusions). From the formability viewpoint, the banded ferrite-pearlite microstructure is not very suitable, Fig. 6. Steels with higher carbon levels contain largely pearlite colonies with ferrite network along prior austenite grain boundaries. As this is a two-phase microstructure, its formability is generally lower than that of pure ferrite. For good formability it is desirable to obtain very fine lamellar structure of pearlite (sorbite).

Incorrect setup of the crystallizer, the heat-treating equipment (patenting) or the cooling equipment (controlled cooling of RW) may result in undesirable phases: ferrite, bainite or martensite forming locally or throughout the wire cross-section. Suitable microstructure and grain size are the basis of high formability of RW without the need for annealing between operations.

5. COST-ORIENTED FMEA OF THE MANUFACTURING PROCESS FOR WIRE DRAWING

The modified calculation of risk priority number RPN\(_C\) was used in FMEA of producing spring wire in a continuous wire rod rolling mill. First, the conventional process FMEA was conducted and then the RPN\(_C\) values were calculated for selected manufacturing sub-processes (wire cleaning, preparation and soaking of billets, wire rolling, wire cooling and finishing). The results were compared. Table 1 lists selected defects of drawn spring wire. Their causes are related to deficiencies of individual manufacturing processes or sub-processes. Each defect is listed with its original risk priority number and with a converted RPN\(_C\), which takes into account cost items related to occurrence of the defect.

Calculation of cost items may be demonstrated for billets burnt in a furnace due to high calorific value of natural gas. The RPN\(_C\) value is then CZK 208,350. This reflects the severity of the defect (V = 6), probability of occurrence (PV = 2) and probability that the defect will be revealed prior to or after delivery to customer (PO = 0.85 and P\(_{\bar{O}}\) = 0.15, respectively). The risk priority number also reflects costs incurred if the defect...
occurs. As burnt billets represent an irreparable defect and the entire batch will be scrapped, the following cost items were considered:

- if defect is revealed prior to delivery to customer: full production costs of one tonne of wire, including the costs of scrapping
- if defect is revealed after delivery to customer: costs of compensatory performance (delivery of a new batch), labour cost of handling the complaints, cost of repair.

Table 1 Evaluation of drawn wire defects

<table>
<thead>
<tr>
<th>Sub-process</th>
<th>Defect</th>
<th>RPN</th>
<th>RPN_C</th>
<th>Rank (RPN)</th>
<th>Rank (RPN_C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Billet cleaning</td>
<td>Dimensional deviations upon grinding</td>
<td>16</td>
<td>3536</td>
<td>8</td>
<td>14</td>
</tr>
<tr>
<td></td>
<td>Edge burrs</td>
<td>24</td>
<td>5094</td>
<td>7</td>
<td>13</td>
</tr>
<tr>
<td></td>
<td>Burnt surface</td>
<td>28</td>
<td>12138</td>
<td>6</td>
<td>12</td>
</tr>
<tr>
<td>Preparation and soaking of billets in continuous wire rod rolling mill</td>
<td>Decarburization</td>
<td>32</td>
<td>120120</td>
<td>5</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>Burning billets in furnace</td>
<td>24</td>
<td>208350</td>
<td>7</td>
<td>5</td>
</tr>
<tr>
<td>Wire rolling</td>
<td>Out-of-specification dimensional tolerance (out-of-specification diameter)</td>
<td>42</td>
<td>163327.5</td>
<td>3</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>Out-of-specification dimensional tolerance (shape defects)</td>
<td>42</td>
<td>246697.5</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>Overlap</td>
<td>32</td>
<td>275784</td>
<td>5</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Rolled-in material</td>
<td>32</td>
<td>275784</td>
<td>5</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Scratch</td>
<td>72</td>
<td>428040</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Rolled-in scale</td>
<td>48</td>
<td>122352</td>
<td>2</td>
<td>9</td>
</tr>
<tr>
<td>Cooling</td>
<td>Out-of-specification microstructure</td>
<td>28</td>
<td>135030</td>
<td>6</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td>Hardening microstructure</td>
<td>28</td>
<td>136825.5</td>
<td>6</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td>Inadequate scale</td>
<td>36</td>
<td>234400.5</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Wire finishing</td>
<td>Wire surface defects (scratching)</td>
<td>24</td>
<td>40995</td>
<td>7</td>
<td>11</td>
</tr>
</tbody>
</table>

In this fashion, all other defects have been examined from the cost items standpoint. These included repair costs (material and labour costs), downtime losses, costs of transport of defective products from the customer, financial penalties and additional payments for failure to meet terms of contract, etc.

Results of implementation of cost-oriented FMEA of the process of production of drawn wire identified a group of defects which require measures reducing the risk of occurrence of such defects or measures minimizing the risk of occurrence of causes of such defects, and thus minimizing the risk of future occurrence of such defects. It is evident that the measures have to be implemented for defects with the highest RPN_C value, as it indicates the potential for increasing production costs and also reveals their potential amount.

6. CONCLUSION

The paper presents an unconventional approach to application of FMEA, taking into account potential costs incurred in case of occurrence of defects. This approach allows organizations to analyze a particular defect in terms of its significance, its impact on the use of the product and undesirable costs incurred by the manufacturing organization, costs which should be eliminated in order to achieve higher profits. This approach was illustrated with practical application to production of drawn wire. This application resulted in identification of those defects which, if present, result in the highest additional costs. These defects should be analyzed further and such measures should be adopted, which minimize the future risk of occurrence of these defects. Unlike the conventional approach to FMEA application, this procedure provided the organization with an overview of all potential defect-related costs and quantification of their proportion of the
total production costs. It is the defect-related cost viewpoint which is neglected in a number of organizations, although it is one of significant aspects in solving problems in and improving their processes and, therefore, the products they deliver.

This paper was created in the project **No. CZ.1.05/2.1.00/01.0040 “Regional Materials Science and Technology Centre”** within the frame of the operation programme “Research and Development for Innovations” financed by the Structural Funds and from the state budget of the Czech Republic.

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