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Comparative Reliability Analysis of Milling Teeth Manufactured by Conventional Cutting Processes and Laser Cladding

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Abstract: This paper presents the estimation of the main reliability indices of two milling teeth types. The comparative analysis referred to milling teeth manufactured by conventional cutting processes, made of 41Cr4 (type I), and milling teeth manufactured by high-productivity welding loading processes, namely, laser cladding (type II). To analyze the distributions of the lifetime data specific to milling teeth types, the correlation coefficient value was considered. Goodness-of-fit analysis indicated that normal distribution was adopted in order to conduct parametric estimates of the reliability indices. Point estimations of the parameters and estimations with 95% confidence intervals of the components' lifetimes were performed, applying the least squares estimation method. Compared to the type II milling teeth, lower values of the reliability function were estimated for the type I milling teeth. The type II milling teeth displayed higher values for the statistical parameters, with a mean of 6 h, while the mean of the failure of the type I milling teeth was 5.2 h. In addition, a more pronounced hazard rate for the type I milling teeth compared to the type II milling teeth was observed.

Keywords: reliability analysis; milling teeth; laser cladding; least squares estimation method

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1. Introduction

Considering the current trends toward significant raw materials and energy savings, the need for environmental protection, and current efforts in the direction of manufacturing sustainable and reliable goods, the emphasis has been put on a new approaches based on the economic design and manufacture of goods. Therefore, modern repair technologies have been developed that consist of reconditioning or manufacturing goods by means of metal deposition processes in areas subject to wear and tear, equipped with intelligent wear protection and self-protection systems, which have been extensively described in the literature [1,2].

Some of the previous research on reconditioning or manufacturing using metal deposition of various products [3,4] has been the basis for the application of these processes for road transportation equipment as well.

Its growth in recent decades has created the need to develop a modern traffic and transportation system that meets the growing demands of freight and passenger traffic. This requires safe and sustainable road infrastructure.

The construction of such infrastructure consists of either building new facilities or often rehabilitating existing ones by applying modern technologies and using high-performance and reliable earthmoving equipment and machinery.

This category of equipment also includes asphalt-stripping milling, which is currently manufactured in a variety of variants that differ from one another in terms of specific characteristics, technology used, nature of the milling material, milling depth, sizes, and shape of the active parts [5].

The main working element is the milling drum, on which the teeth are fastened by means of a support (Figure 1) [5].

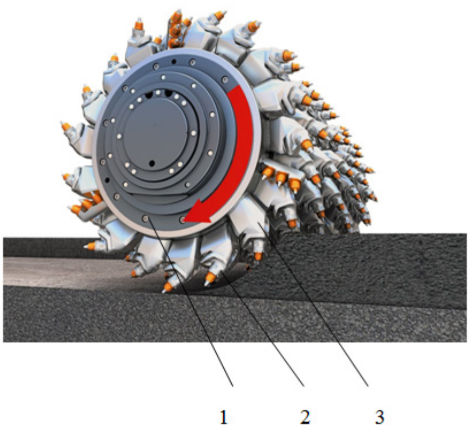

Figure 1. Milling drum: (1) drum; (2) milling tooth; (3) fastening support.

The components of a tooth are shown in Figure 2 [5].

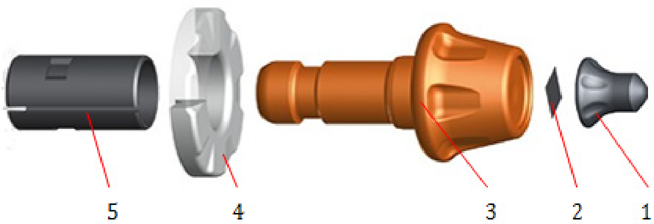

Figure 2. Components of a milling tooth: (1) tungsten carbide tip; (2) brazing tablet; (3) body; (4) wear plate; (5) clamping shank.

During milling, teeth are subjected to intense wear as follows: the tip of the tungsten carbide tooth is subjected to wear abrasion under high pressure, while the body of the tooth is subjected to wear due to its hard contact with the earthworks structure, which eventually leads to a self-locking phenomenon while rotating around their axis and, eventually, to their early decommissioning.

Teeth are currently made of various materials with different geometries, using carbide or diamond inserts, with flat, fixed, or movable active surfaces that work at variable pressures and have different wear resistances [5–7].

The disadvantages of these milling teeth consist in the complexity of the operations required for making the semifinished components of the wear protection systems and in the high costs and low durability, determined by the self-locking rotation, a phenomenon that results in their early decommissioning.

Studies have been conducted in the field of milling teeth reconditioning or manufacturing using various metal deposition technologies [6–11].

A milling tooth (Figure 3) has two active areas, namely, the tungsten carbide tip (1) and the frustoconical section of the milling tooth body (4). The basic design is aimed at increasing wear resistance by welding deposition of annular cords (2) of adequate width and thickness, with high wear resistance and self-locking protection while rotating around their own axis [6,7,12].

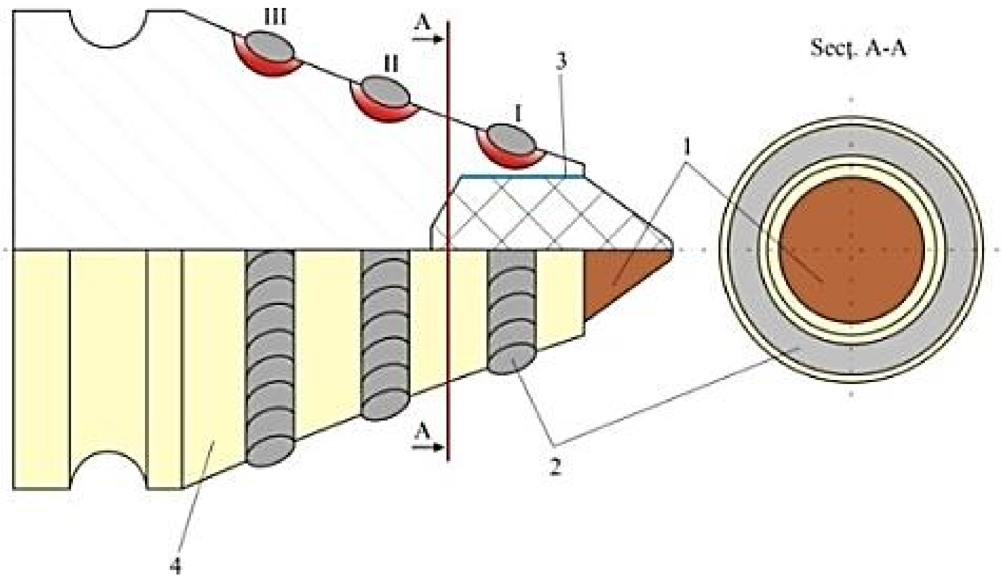

Figure 3. Concept of welding cord deposition on the frustoconical section of the tooth: (1) tungsten carbide tip; (2) annular cords achieved by metal deposition; (3) tungsten carbide tip brazing area in the front hole; (4) frustoconical section of the milling cutter tooth; zone I—first cordon; zone II—third cordon; zone III—second cordon.

Various welding processes are used, such as WIG, MIG-MAG, oxyacetylene flame, laser, with appropriate additives [13–15] to carry out the metal deposition of the frustoconical section of the milling tooth body, the purpose being to develop intelligent anti-wear and anti-lock protection systems when rotating around their axis.

The research presented in this paper describes teeth manufactured using a high-performance, automated, and robotic metal deposition technology in the active area by means of laser and powder. This was based on the research presented in papers such as [16–18].

The reliability estimation is an important approach for every product, because it allows to minimize the unplanned downtime cost, to reduce the defective parts, to improve the performance of the product or system, and to implement the optimal maintenance process [19–22].

The literature references related to the reliability estimation of milling teeth manufactured by metal deposition are rather scarce. In this respect, this paper refers to the reliability indices prediction of different types of milling teeth. The analyzed milling teeth were made using a high-performance, automated, and robotic welding loading technology in the active area with laser and powder. Milling was equipped, and testing was conducted in operation. Taking into account that road rehabilitation requires millings equipped with a high number of teeth, we considered that it would be appropriate to achieve a comparative study of the milling teeth made by conventional procedures and those made by a modern, productive, and actual process—laser cladding.

2. Materials and Methods

2.1. Research on the Metal Deposition on the Frustoconical Surfaces of Milling Teeth Tips Using Laser and Alloy Powders

The research consisted of a series of experiments on the deposition of annular layers on the whole frustoconical surface of a particular type of milling tooth used for asphalt stripping, using alloyed powder. A robotic welding cell was used for this purpose on which a laser metal deposition head was fitted (Figure 4).

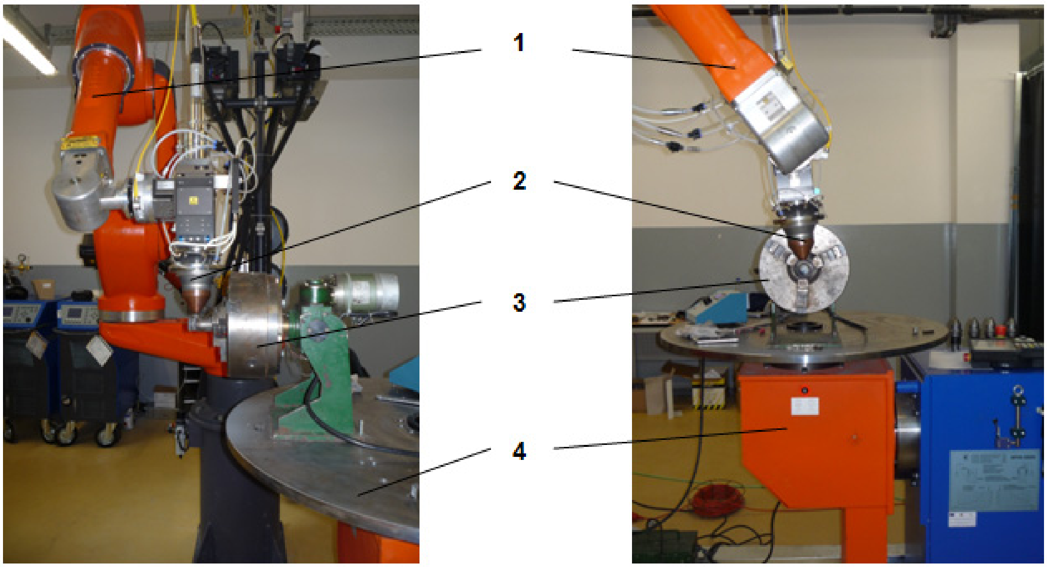

Figure 4. Experimental assembly used for laser metal deposition using a robotic cell: (1) welding robot; (2) processing head-laser deposition module; (3) tooth rotating and positioning device; (4) rotating and positioning table.

Four variants of metal deposition on teeth were used to establish the optimal working parameters required to achieve the deposition of a homogeneous layer of powders with high wear resistance on the whole frustoconical surface of the tooth (Figure 5). We began with the deposition of two distinct cords: one on the minimum and the other on the maximum diameter of the frustoconical section of the tooth (Figure 5a). This was followed by depositions of adjacent cords that partially overlapped, with different overlapping ratios: one-third (Figure 5b) and two-thirds (Figure 5c). Finally, the surface in Figure 5d was achieved by optimizing the loading parameters.

(**a**) (**b**) (**c**) (**d**)

Figure 5. Variants of alloyed powder and laser metal deposition on the frustoconical section of the tooth; (**a**) two cord metal deposition; (**b**) metal deposition with a one-third overlap; (**c**) metal deposition with a two-third overlap; (**d**) optimized metal deposition.

Cross-sections of the depositions using a laser with alloyed powders on the tips of the teeth were analyzed by metallographic means in the specific deposition areas: basic metal (BM), heat-affected zone (HAZ), and deposited metal (DM) (Figure 6).

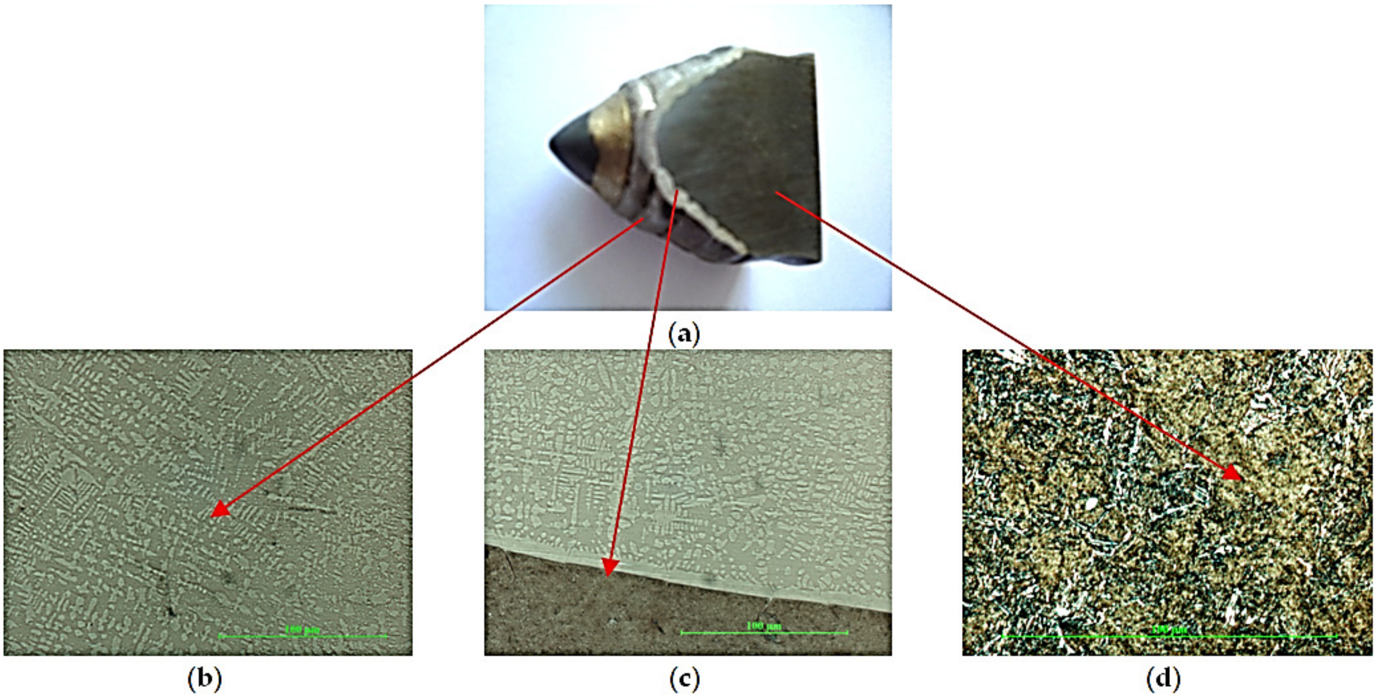

Figure 6. Views of the macro- and microstructural analyses of the powder and laser metal deposition area: (**a**) milling tooth macrostructure; (**b**) deposited material (DM), 100× magnification; (**c**) transition area (TA), 50× magnification; (**d**) base material (BM), 50× magnification.

The microhardness determinations of the deposition area (DM) revealed increased values compared to the body of the tooth (BM), close to those of the tungsten carbide tip (Table 1). This allowed for a symmetrical wear of the tooth body in operation and facilitated rotation around their own axis, avoiding self-locking and resulting in better tooth durability.

Table 1. The microhardness determinations in the characteristic areas.

No. of Fingerprint	Microhardness HV_{01}			HRC Microhardness Equivalent		
	BM	HAZ	DM	BM	HAZ	DM
1	320	502	590	32.1	49.5	54.9
2	322	469	588	32.4	47	54.8
3	333	478	576	33.7	47.7	54.2
4	327	498	615	33	49.2	56.2
5	324	469	593	32.6	47	55.1

2.2. The Reliability Estimation of the Milling Teeth

The analysis consisted of estimating the reliability of the milling teeth manufactured through various loadings by welding procedures.

The analyzed milling teeth were as follows:

1. Type I: Milling teeth manufacturing by a conventional cutting process made of 41Cr4;
2. Type II: Obtained through loading by laser cladding.

Given the rough working conditions, the milling machine was stopped at regular intervals (approximately 2 h) for cooling and inspection. The periodic inspection, in this case, consisted of the thorough analysis of each tooth (after flushing with water), estimating the wear degree of each, and the manner in which it was produced. Even if the degree of wear in some milling teeth was high, the teeth were kept until the end of the working cycle (8 h). The experimental data were obtained over a period of one month, on a milling equipped with 50 teeth, in operation for the rehabilitation of a section of asphalt road.

There are a wide variety of reliability engineering tools that could be applied to estimate the reliability indices of the products or systems [23–28].

Reliability prediction applying standard methods typically utilize a probability distribution function (pdf) to describe the time to failure of a material, component, or system. Once one adequate distribution is identified from the lifetime observed, reliability may be estimated as a function of time [29].

In order to validate the statistical model, there are available the goodness-of-fit tests. The correlation coefficient approach was used to estimate the parameters for the best-fitted statistical distributions.

The most popular methods are least squares (LS) and maximum likelihood estimation (MLE), which are both implemented in reliability estimation.

Given a continuous random variable X, it was specified that [23,24,30,31]:

- $f(x)$ is the probability density function (PDF);
- $F(x)$ is the cumulative density function (CDF).

If X is a continuous random variable, then the probability density function of X is a function $f(x)$, such that for two numbers, a and b, with $a \leq b$:

$$P(a \leq X \leq x) = \int_0^x f(x)dx. \quad (1)$$

The cumulative distribution function is a function $F(x)$ of a random variable X and is defined for a number x by:

$$F(x) = P(X \leq x) = \int_{0,-\infty}^x f(x)dx. \quad (2)$$

Specific to normal distribution, the main indices are given by the following equations [23,24,30,31]:

$$f(t) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{(t-\mu)^2}{2\sigma^2}}, \quad (3)$$

$$F(t) = \frac{1}{\sigma\sqrt{2\pi}} \int_{-\infty}^t e^{-\frac{(t-\mu)^2}{2\sigma^2}}, \quad (4)$$

$$R(t) = \frac{1}{\sigma\sqrt{2\pi}} \int_t^\infty e^{-\frac{(t-\mu)^2}{2\sigma^2}}, \quad (5)$$

$$h(t) = \frac{e^{-\frac{(t-\mu)^2}{2\sigma^2}}}{\int_t^\infty e^{-\frac{(t-\mu)^2}{2\sigma^2}}} \quad (6)$$

where μ is the mean, and σ is the standard deviation.

Suppose the observations of random variable $(x_1, y_1), (x_2, y_2), \ldots, (x_i, y_i), \ldots, (x_n, y_n)$. If a straight line is fitted such that the sum of the squares of the vertical observations of observed y_i from this line is minimum, then such a line is said to have the least squares property. The sum of squares is defined as [23]:

$$S = \sum_{i=1}^n d_i^2 = \sum_{i=1}^n [y_i - (ax_i + b)]^2 = \min. \quad (7)$$

The equation of the fitted line is given by:

$$y = ax + b \quad (8)$$

It is obtained by:

$$S = [y_1 - (ax_1 + b)]^2 + [y_2 - (ax_2 + b)]^2 + \ldots + [y_i - (ax_i + b)]^2 + \ldots + [y_n - (ax_n + b)]^2 = \min . \quad (9)$$

The condition is:

$$\begin{cases} \frac{\delta S}{\delta a} = 0, \\ \frac{\delta S}{\delta b} = 0. \end{cases} \quad (10)$$

Substituting the values, it is obtained by the equation system:

$$\begin{cases} -2x_1[y_1 - (ax_1 + b)] - 2x_2[y_2 - (ax_2 + b)] - \ldots - 2x_i[y_i - (ax_i + b)] - \ldots - 2x_n[y_n - (ax_n + b)] = 0, \\ -2[y_1 - (ax_1 + b)] - 2[y_2 - (ax_2 + b)] - \ldots - 2[y_i - (ax_i + b)] - \ldots - 2[y_n - (ax_n + b)] = 0. \end{cases} \quad (11)$$

In this respect, the parameters are defined as:

$$\begin{cases} a\sum_{i=1}^{n} x_i^2 + b\sum_{i=1}^{n} x_i - \sum_{i=1}^{n} x_i y_i = 0, \\ a\sum_{i=1}^{n} x_i + nb - \sum_{i=1}^{n} y_i = 0. \end{cases} \quad (12)$$

$$a = \frac{\sum_{i=1}^{n} x_i y_i - \frac{1}{n}\sum_{i=1}^{n} x_i \sum_{i=1}^{n} y_i}{\sum_{i=1}^{n} x_i^2 - \frac{1}{n}\left(\sum_{i=1}^{n} x_i\right)^2}, b = \frac{1}{n}\left(\sum_{i=1}^{n} y_i - a\sum_{i=1}^{n} x_i\right). \quad (13)$$

The parametric estimation and inferential analysis of different constructive types of milling teeth were statistically conducted using Minitab 17 software (Minitab LLC, State College, PA, USA) [32].

Parametric analysis of the distribution, in particular the least squares estimation, was performed referring to the estimation of reliability indices of the milling teeth under study. With a confidence interval (CI) of 95%, the point estimation of reliability and unreliability functions, means time to failure (MTTF), and hazard rates were estimated.

3. Results and Discussion

Based on the lifetime data, a parametric analysis of the distributions was applied. The most frequent distributions were considered in order to analyze the goodness-of-fit. Weibull, lognormal, exponential, and normal probability distributions were considered for parametric distribution analysis. The results of goodness-of-fit test expressed by Pearson's correlation coefficient applying the least squares estimation method and the statistical models are outlined in Table 2 and Figure 7.

Table 2. Goodness-of-fit for milling teeth.

Distribution	Correlation Coefficient	
	Type I	Type II
Weibull	0.84	0.88
Lognormal	0.90	0.91
Exponential	-	-
Normal	0.90	0.93
3-Parameter Weibull	0.84	0.88

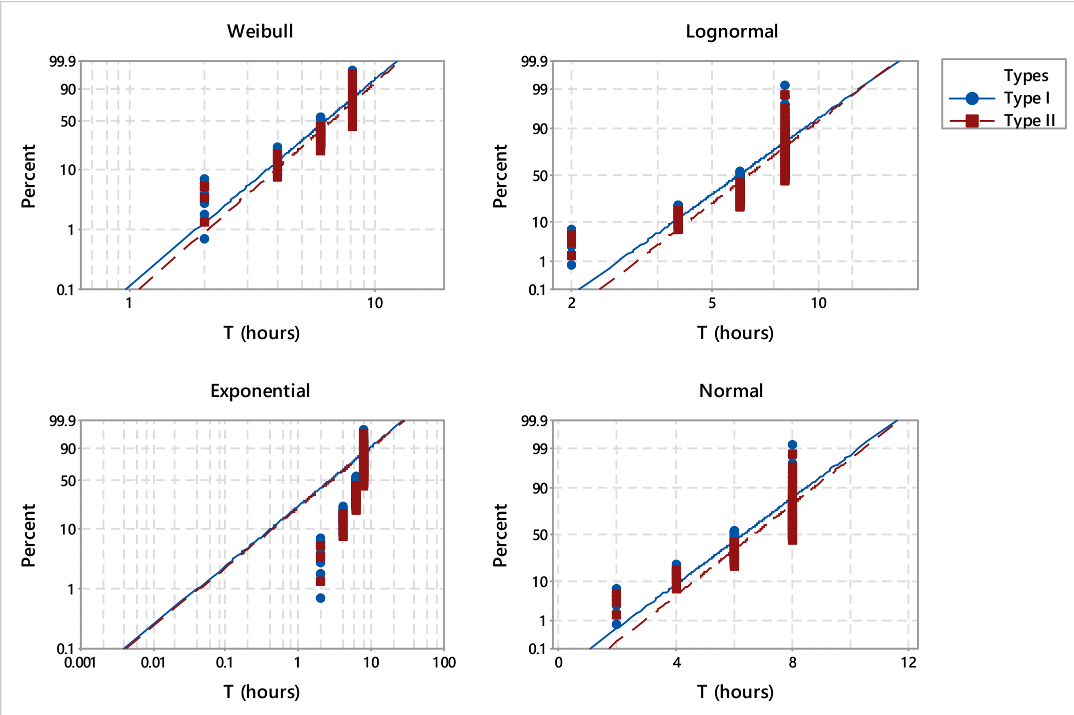

Figure 7. The probability plots of lifetime milling teeth.

A low statistic value demonstrates that the lifetime data did not fit the supposed distribution. Comparing the values of the correlation coefficients, it can be observed that they were comparable except for the exponential distribution. In order to estimate the reliability indices specific to different types of milling teeth, the normal distribution was selected.

To highlight the differences between the two types of milling teeth, the analysis consisted of comparing the main reliability indicators. The estimated reliability functions, hazard rate functions, and parameters estimate of the milling teeth under study are illustrated in Figures 8 and 9. In addition, the descriptive statistics of the type I and type II milling teeth for the considered distribution are synthesized in Tables 3 and 4.

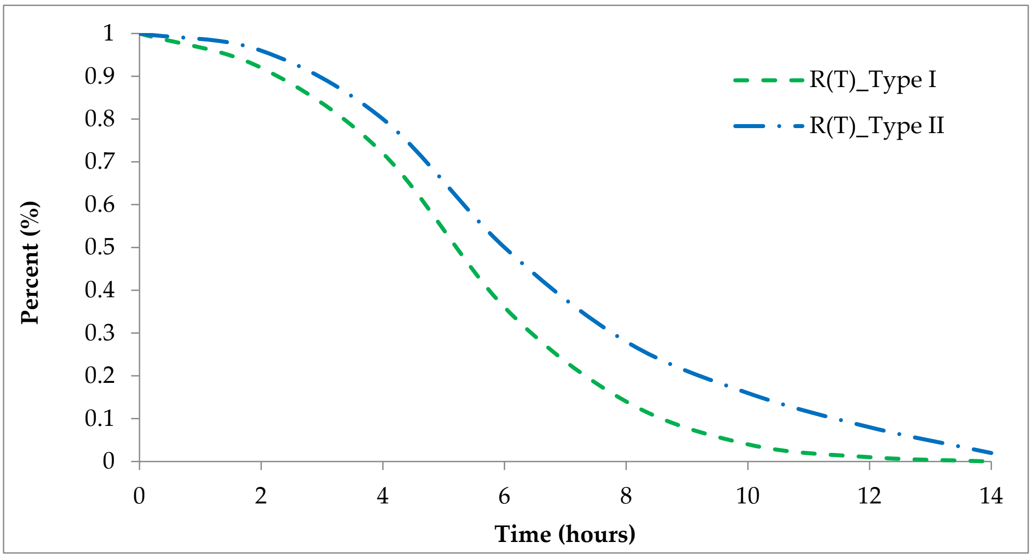

Figure 8. Comparative analysis of the reliability functions for the analyzed milling teeth.

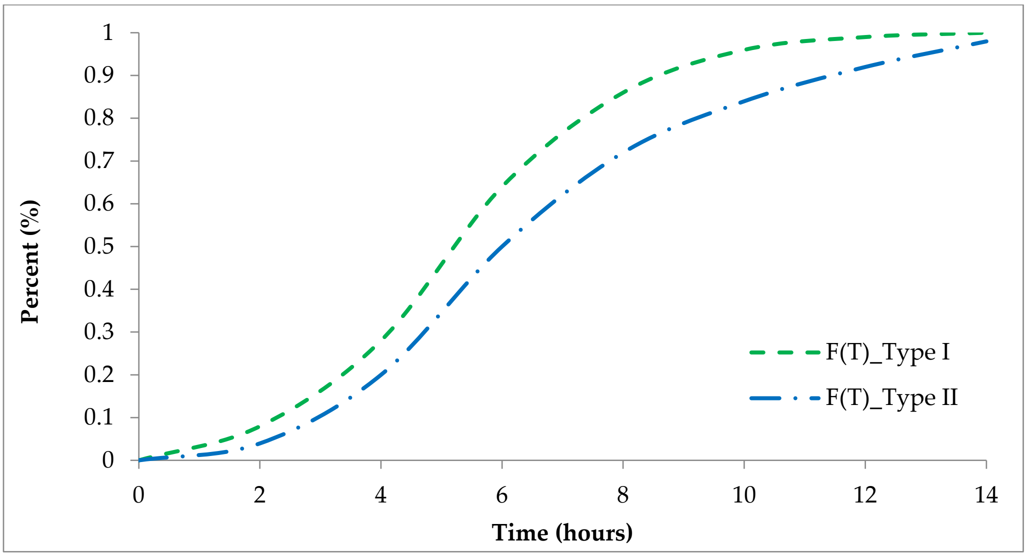

Figure 9. Comparative analysis of the unreliability functions for the analyzed milling teeth.

Table 3. Estimation of parameters for the type I milling teeth.

Parameter	Estimate	Standard Error	95% Normal CI	
			Lower	Upper
Mean (MTTF)	5.21	0.16	4.87	5.54
Standard Deviation	1.70	0.10	1.48	1.91
Median	5.21	0.16	4.87	5.54
First Quartile (Q1)	3.81	0.18	3.45	4.18
Third Quartile (Q3)	6.98	0.18	6.62	7.35
Interquartile Range (IQR)	3.16	0.14	2.88	3.45

Table 4. Estimation of the parameters for the type II milling teeth.

Parameter	Estimate	Standard Error	95% Normal CI	
			Lower	Upper
Mean (MTTF)	6.03	0.16	5.70	6.35
Standard Deviation	1.96	0.10	1.75	2.16
Median	6.03	0.16	5.70	6.35
First Quartile (Q1)	4.41	0.17	4.06	4.76
Third Quartile (Q3)	8.45	0.17	8.10	8.80
Interquartile Range (IQR)	4.03	0.14	3.75	4.31

With a 95% confidence interval, the main statistic parameters indicate an MTTF of type I milling teeth equal with the median value, namely, 5.21 h. Moreover, the standard deviation of 1.7 h allowed for making decisions at the right time.

Specific to the type II milling teeth, the statistic parameters indicated a mean value of 6 h and a standard deviation of 1.96 h.

Specific to the type II milling teeth, the 1st quartile (Q1) was 4.4 h, the third quartile (Q3) was less or equivalent to 8.4 h, and the estimated interquartile range was 4 h. Whereas the type I milling teeth presented in the 1st quartile (Q1) with a value of 3.8 h, the third quartile (Q3) was smaller or equivalent to 6.9 h, and the estimated interquartile range was approximately 3.1 h. In addition, taking into account the reliability objectives, the most likely time to failure can be estimated based on the plot of the reliability or unreliability functions.

All elements of a pick are subjected to wear depending on the material to be milled [33].

The numerical estimation method facilitates the analysis of the influence of the specific hazard rate of the milling teeth on the wear aspects. Moreover, from the point of view of the wear phenomenon, based on the curves presented in Figure 10, there was an accentuated phenomenon of damage to the tooth of the type I milling teeth. Compared to type I, which showed an accentuated tendency of a hazard rate, the type II hazard rate tendency showed smooth variations over the working time.

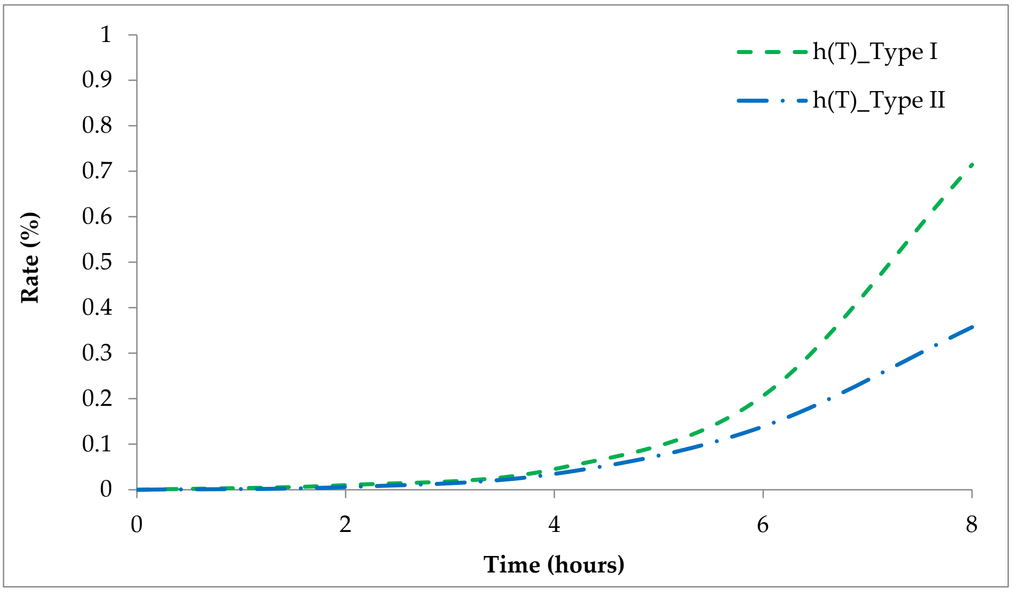

Figure 10. Comparative analysis of the hazard rate functions for the analyzed milling teeth.

The authors of this paper also achieved other findings related to the reliability of milling teeth manufactured by metal deposition using other welding procedures as well (different from the one described in this paper) on other types of teeth used for road structure stripping such as in [1,3,4,7–9,11,14,16,34,35]:

- WIG welding procedure—with an automatic filler;
- WIG welding procedure with a tubular rod;
- MIG/MAG welding procedure—cold metal with a tubular wire.

The analysis of various milling teeth manufactured by the processes described above shows that the analyzed teeth also had high reliability compared to the teeth manufactured by conventional cutting procedures.

4. Conclusions

The overall comparative analysis revealed that type II milling teeth exhibited superior reliability compared to the type I milling teeth. However, to achieve a percentage of 75% of the standard level, the reliability was approximately 6 h for the type II milling teeth under study compared to 5.2 h specific to the type I milling teeth. This means that it would be useful to perform maintenance actions.

The behavior of the milling teeth varied according to different factors: working conditions, asphalt structure, constructive characteristics of teeth, working parameters, stress level, etc. Analyzing the reliability of the milling teeth obtained through the analyzed procedures, we found that the evolution of wear was exacerbated after 6 h of operation, most of it being caused by self-locking during rotation, thus resulting in a preferential wear (i.e., on one side only).

Using laser metal deposition, we found that wear due to self-rotation locking, adhesion, and abrasion decreased, which resulted in longer operating times in conditions of economic efficiency. The research conducted also justifies an improvement in operating performance.

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