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Automotive leaf spring design and manufacturing process improvement using failure mode and effects analysis (FMEA)

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Abstract

Nowadays human safety and comfort are the most considerable parameters in designing and manufacturing of a vehicle, that is why every organization ensures the quality and reliability of components used in the vehicle. Leaf spring is also a component of vehicle which plays an important role in human safety and comfort. It acts as a structural member and an integral part of suspension system. It is important to eliminate the failures in designing and manufacturing process of leaf springs because of its importance in functionality and safety of vehicle. In this research, failure mode and effects analysis has been used to analyze and reduce the risks of 42 possible failures that can occur in automotive leaf spring. It starts from determining, classifying, and analyzing all potential failures and then rating them with the help numeric scores. The four numeric scores namely severity, occurrence, detection, and Risk Priority Number (RPN) are used to find the high potential failures of semi-elliptical leaf springs. In the end, actions are recommended for RPN greater than 250, to increase quality and reliably of product.

Keywords

FMEA, leaf spring, manufacturing, process improvement, RPN

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Introduction

History of leaf springs goes back to the Romans who decided that their chariots need suspension system when riding on irregular surfaces. Leaf springs are the simplest form of suspension spring commonly used in heavy-duty vehicles and are made from spring steel of varying sizes packed upon one another as shown in Figure 1. There are many problems which a leaf spring manufacturing organization can face in designing and manufacturing process of a product. The increasing competition in the industry is forcing the manufacturers to adopt several quality improving tools. Failure mode and effects analysis (FMEA) is a tool for manufacturing organization to begin looking at their problems and correcting them while improving the quality and reliability of product. FMEA looks at all realistic potential problems and then rate those problems with a numeric score.

Literature review

There have been studies done on failure and risk analysis using FMEA in automotive, aeronautical, and nuclear industries. Dutta et al.[1] studied all the possible failures that can occur in analogy alarm trip units at electronic component level using FMEA. Gundewar and Kane[2] did fuzzy FMEA analysis of electromechanical induction motor and

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Figure 1. Leaf spring.

found that the electrical faults have higher Risk Priority Number (RPN) as compare to mechanical. Bakhshi et al.[3] studied the failure consequences of corrosion mitigation in electronic system. Cost-based FMEA was performed showing the risk scenarios and control plan to get return on investment. Nataraj and Thillikkani[4] studied failures of leaf springs used in trucks using visual inspection and scanning electron microscope. They proposed a design in which optimization of failure parameters and improvement in fatigue life was achieved.

Koomsap and Charoenchokdilok[5] studied that there was less involvement of customers in developing FMEA. Kano model was to make it more customer oriented. Rezaee et al.[6] implemented two techniques namely fuzzy cognitive map (FCM) and process failure mode & effects analysis (PFMEA) to accurately find and prioritize potential failure in production process. Kim and Zuo[7] developed a model to show functional relationship between severity, occurrence, and detectability. Peeters et al.[8] performed fault tree analysis (FTA) on a manufacturing system to get the set of failure modes and then FMEA was performed to evaluate these failure modes. Spreafico et al.[9] reviewed the research done on FMEA and concluded different problems in FMEA. Sutrisno et al.[10] modified the FMEA by combining Taguchi loss and entropy function into decision support model to evaluate the criticality level of waste in operation of manufacturing process. Baynal et al.[11] combined grey relational analysis (GRA) and FMEA to improve the RPNs. Liu et al.[12] studied improved methodology to find RPNs based on fuzzy measure and fuzzy integral method. Fragoudakis et al.[13] investigated the leaf spring manufacturing process and noted mechanical properties at different stages. The effect of each manufacturing processes on the fatigue life was verified by experimental Wöhler curves. Haigh diagrams and the factors of mean stress sensitivity are used to calculate fatigue life. Fonte et al.[14] studied failure mode analysis of two diesel engine crankshafts and found that fatigue fracture was the most primary failure mode in crankshafts. Lijesh et al.[15] applied FMEA to identify the various failure modes in different passive magnetic bearings.

Sellappan and Palanikumar et al.[16] proposed that when identical values of RPNs were produced than the failure mode with smaller RPN range is more severe. Kolich[17] used FMEA technique to design comfortable driver seat in automotive sector. Feili et al.[18] applied FMEA technique on geothermal power plants by utilizing XFMEA software. Sellappan et al.[19] proposed modified RPN prioritization method to solve the problem of identical and average values of RPN. Statistical analysis was done by using MINITAB program and it showed that the proposed methodology was statistically useful for prioritizing failure modes. Vinodh and Santhosh[20] applied design failure mode & effects analysis (DFMEA) and PFMEA in automotive industry. Xiao et al.[21] proposed a minimum cut set theory-based method to consider the impact of multiple failures and suggested that for non-repairable system weights of severity and occurrence should be more than detectability. The aim of this research is to implement FMEA in automotive leaf spring manufacturing organization. This research is an attempt to achieve the following objectives:

1. Design FMEA of leaf spring
2. Process FMEA of leaf spring

FMEA will be carried out in areas where failures are likely to be happening in high rates. These areas directly affect the reliability of the product and indirectly support the success of any organization.

Literature review shows that FMEA is a well-defined technique and has been used in many engineering systems to increase the reliability, quality, and safety of a system. It is carried out in areas where failures are likely to be happening in high rates. These areas directly affect the reliability of the product and indirectly support the success of any organization. The aim of this research is to implement design and process FMEA in automotive leaf spring manufacturing organization. This study uses FMEA to analyze and reduce the risks of 42 possible failures that can occur in automotive leaf spring designing and manufacturing processes.

Case study

A case has been conducted in automotive leaf spring manufacturing industry located in Muridke, District Sheikhupura, Pakistan. This industry manufactures leaf springs for original equipment manufacturer (OEMs) like Toyota, Pak Suzuki, Master Motors, and Sazgar. The departments involved in this study are R&D, production, and quality control. All the technical data are collected from literature review, field study, and surveys. Discussions with experts and professionals also helped us in collecting and analyzing data. Sample size and time frame of this research has been given in Tables 5 and 7.

To make decisions, Delphi technique is also used with FMEA. This technique is helpful for consensus within a group of experts of different departments as this was not possible to arrange joint meeting for brainstorming and problem-solving. For all failures, a questionnaire was developed, which contained all different points needed to be discussed, such as failure causes, effects, occurrence, severity, and detection. After that, results were discussed and analyzed with experts for individual evaluation of all failures. This process was repeated several times to reduce bias and standard deviation.

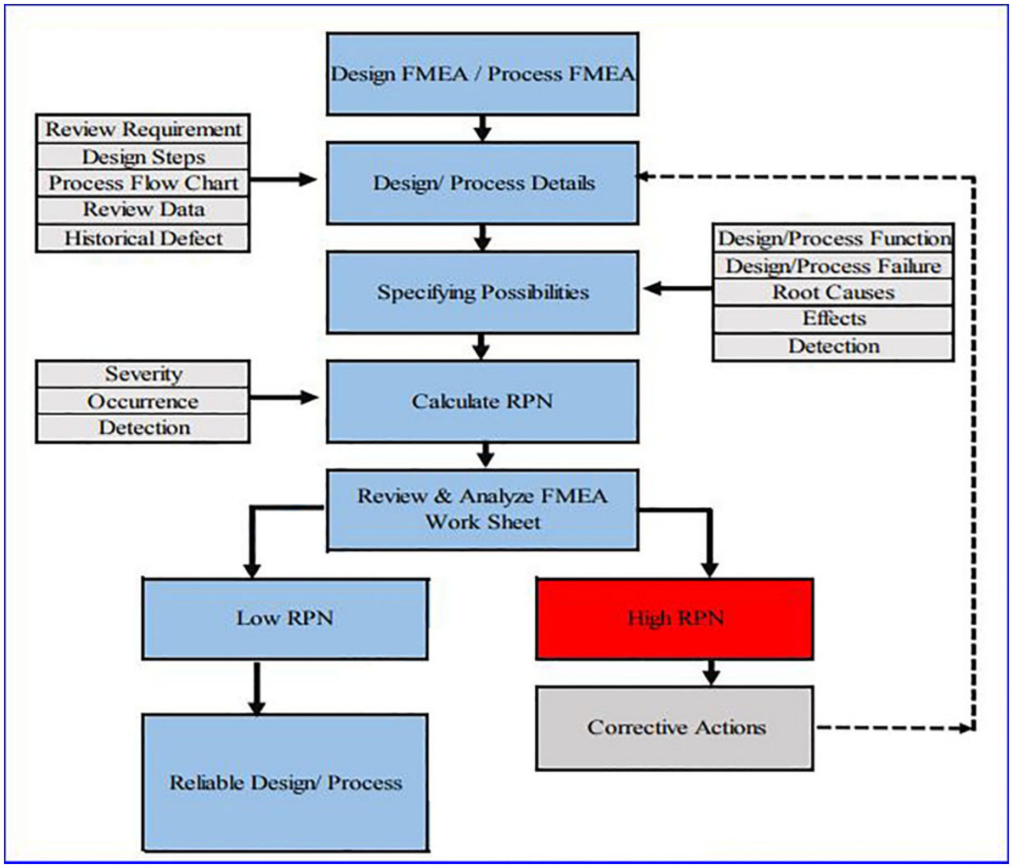

Figure 2. Methodology to develop FMEA. FMEA: failure mode and effects analysis.

Table 1. Severity.

Severity (*S*)	
Rank	Evaluation criteria
10	Failure of leaf spring assembly or failure in critical process that can endanger the safety of passenger and cause fatal accident without prediction
9	Failure of leaf spring assembly or failure in critical process that can endanger the safety of passenger and cause fatal accident with predictability
8	Failure that causes 100% loss of primary performance and function of leaf spring assembly and lead to serious accidents or failure that can disturb the production line. Outflow failure results in rejection at user end and large portion of product have to be reworked
7	Failure in a design or process that can reduce performance and function of leaf spring assembly and lead to serious accidents. A portion of product must be reworked with repair time more than 2 h
6	Failure that can reduce performance and function of leaf spring assembly. A small portion of product have to be reworked with repair time more than 1 h
5	Affected leaf springs are usable or operable but at a reduced level of performance or function. Product can be reworked without any material loss with repair time less than 1 h
4	Lead to multitudes of warranty claims against leaf spring assembly with respect to fit and finish, appearance, noise in use or operation, feeling, and so on
3	Lead to warranty claims against leaf spring assembly with respect to fit and finish, appearance, noise, and feeling in use or operation, and so on
2	Noise in use or operation. Defect noticed by very limited users
1	No visible effect or effect can be ignored

Methodology

The general steps to develop FMEA are given in Figure 2. It starts from defining the functions, possible failure modes, and their potential effects. Severity, occurrence, detectability, and RPN are used to evaluate FMEA and evaluation criteria are given in Tables 1 to 4, respectively. Severity tells us how bad the failure can be? If severity is 1 it means

Table 2. Occurrence.

Occurrence (O)			
Rank	Evaluation	Design	Process
10	Frequently occur	≤100 per hundred pieces	≤100 per 3600 pieces
9		≤50 per hundred pieces	≤50 per 3600 pieces
8	High incidence rate	≤20 per hundred pieces	≤20 per 3600 pieces
7		≤10 per hundred pieces	≤10 per 3600 pieces
6	Moderate incidence rate	5 per hundred pieces	5 per 3600 pieces
5		4 per hundred pieces	4 per 3600 pieces
4	Low incidence rate	3 per hundred pieces	3 per 3600 pieces
3		2 per hundred pieces	2 per 3600 pieces
2	Almost never occurs	1 per hundred pieces	1 per 3600 pieces
1		0 per hundred pieces	0 per 3600 pieces

Table 3. Detection.

Detection (D)	
Rank	Evaluation criteria
10	Failure cannot be detected before delivery to customer. No process controls available to detect failure
9	Failure is likely to be flowed out to customer. Process controls currently in place cannot detect failure
8	Extremely difficult to be detected failure before shipping. Process control currently in place will probably not detect failure
7	Failure is detectable by periodic sampling inspection. Difficult to detect failure by current process control. Failure can be detected by periodic sampling inspection. Process controls currently in place have poor chance of detection
6	Failure can be detected by regularly conducted sampling inspection or 100% visual inspection. Process controls currently in place may overlook failure
5	Failure can be detected by 100% final inspection (manual). Process controls currently in place may detect failure
4	Failure can be detected by 100% final inspection through checking fixture or gauge. Failure can be detected in the subsequent process. Process controls currently in place can detect failure
3	Failure can be detected in the subsequent process. Process controls currently in place can detect failure (monitor trends by using statistical process control in addition to 100% inspection and so on)
2	Failure can be detected within the process. Process control such as QA devices and so on is in place for 100% inspection with automatic error detection feature
1	Detection is easy and no attention is required. Process control system such as QA device and so on is in place for 100% inspection with automatic error detection and removal features

Table 4. Risk Priority Number.

RPN = $S \times O \times D$		
Sr#	RPN	Response
10	401–1000	Top priority
9		Immediate measures required
8	250–400	High priority
7		Implement measures
6	101–249	Moderate priority
5		Monitor the occurrence of a failure mode and implement measures accordingly
4	11–100	Low priority
3		Implement measures where time and resources allow
2	1–10	Accept as a remaining risk
1		No further measures required

RPN: Risk Priority Number.

no effect and if severity is 10 it means seriously safety hazard. Occurrence tells us how often particular failure can occur? If occurrence is 1 it means rare event and if occurrence is 10 it means failure is almost inevitable. Detectability tells us how often current controls can detect the failure? If detection is 1 it means system will certainly detect the failure and if detection is 10 it means system cannot detect the failure. RPN can be found by multiplying severity, occurrence, and detectability:

$$\mathrm{RPN} = S \times O \times D \tag{1}$$

If RPN goes down, it means that the problem will happen less and will be easy to catch and prevent. In this research, FMEA is applied on product or process to reduce failures, to achieve better customer satisfaction, to increase quality and reliability.

Design FMEA of leaf spring

The following elements must be known in semi-elliptical leaf spring as shown in Figure 3.

The prerequisite step involved in design of leaf spring[22] is shown in Figure 4. These functions are then used in Table 6.

Table 5. No. of rejections in development phase of leaf spring.

Month	No. of samples	Rejection	NG thickness	NG span length	NG deflection	NG camber	Bush distortion	Nut/bolt fracture	NG eye	NG tapper	NG edge cutting
February 2017	20	34	1	2	11	2	4	4	7	0	3
March 2017	20	13	0	0	2	0	0	0	11	0	0
April 2017	20	2	0	1	0	1	0	0	0	0	0
May 2017	20	0	0	0	0	0	0	0	0	0	0
June 2017	20	2	0	1	0	1	0	0	0	0	0
July 2017	20	0	0	0	0	0	0	0	0	0	0
August 2017	10	0	0	0	0	0	0	0	0	0	0
September 2019	20	12	0	1	6	0	1	0	0	4	0
October 2019	20	1	0	0	0	0	0	0	0	1	0
November 2019	20	0	0	0	0	0	0	0	0	0	0
December 2019	10	0	0	0	0	0	0	0	0	0	0
Total	200	64	1	5	19	4	5	4	18	5	3

NG: Not Good.

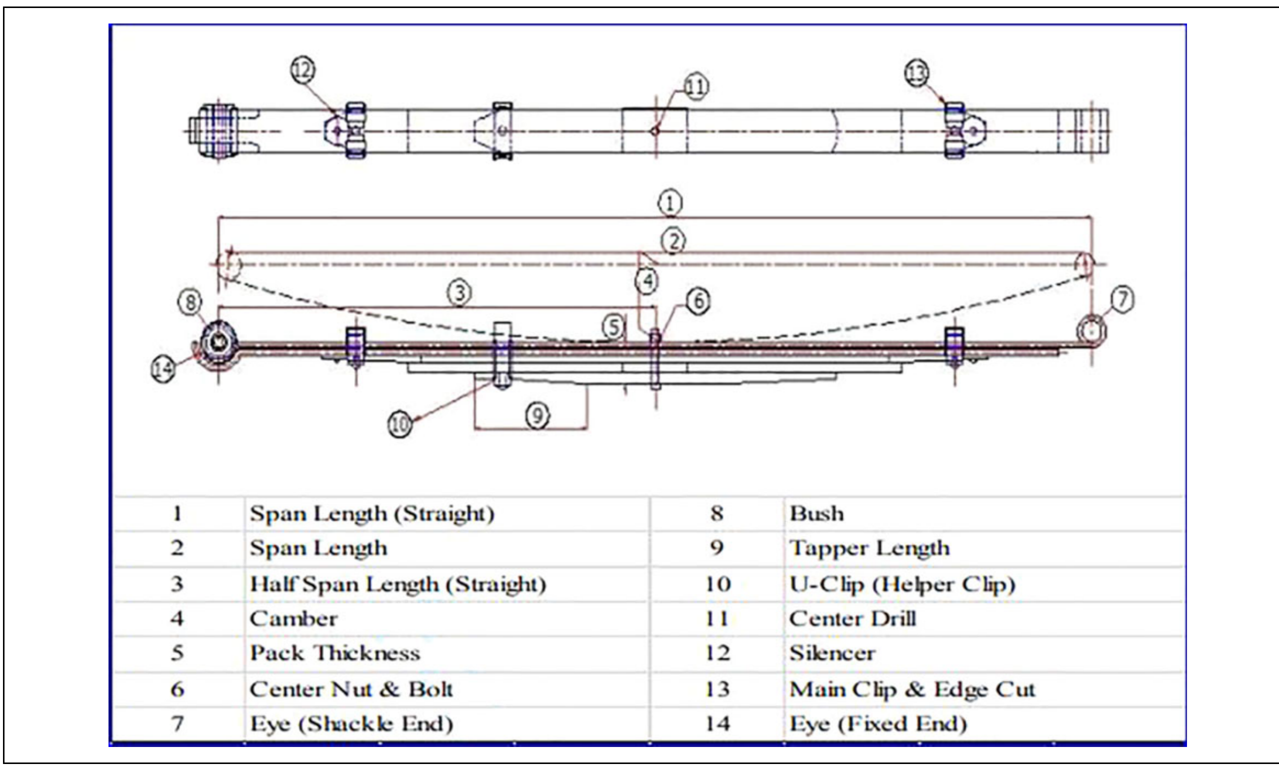

Figure 3. Brief description of design elements.

The design FMEA focuses on design stages involved form material selection to final product. All the ratings are developed from knowledge of design and then rating to failures are given according to predetermined scale. Severity ratings are given according to potential effects from Table 1. Potential causes of failure modes are derived from fishbone diagrams and detection are developed by analysis of measurement system. Potential failure modes are taken from historical defect data which include quality defect reports by customers, inhouse rejections, and inhouse repair orders as given in Table 5. Potential effects are derived by focusing on output of each step.

After collecting all the information DFMEA will be started as given in Table 6. The rating of severity, occurrence, and detection are given by team from design knowledge and predetermined scale.

PFMEA of leaf spring manufacturing process

Leaf spring manufacturing process flowchart is shown in Figure 5. Leaf spring manufacturing process starts from

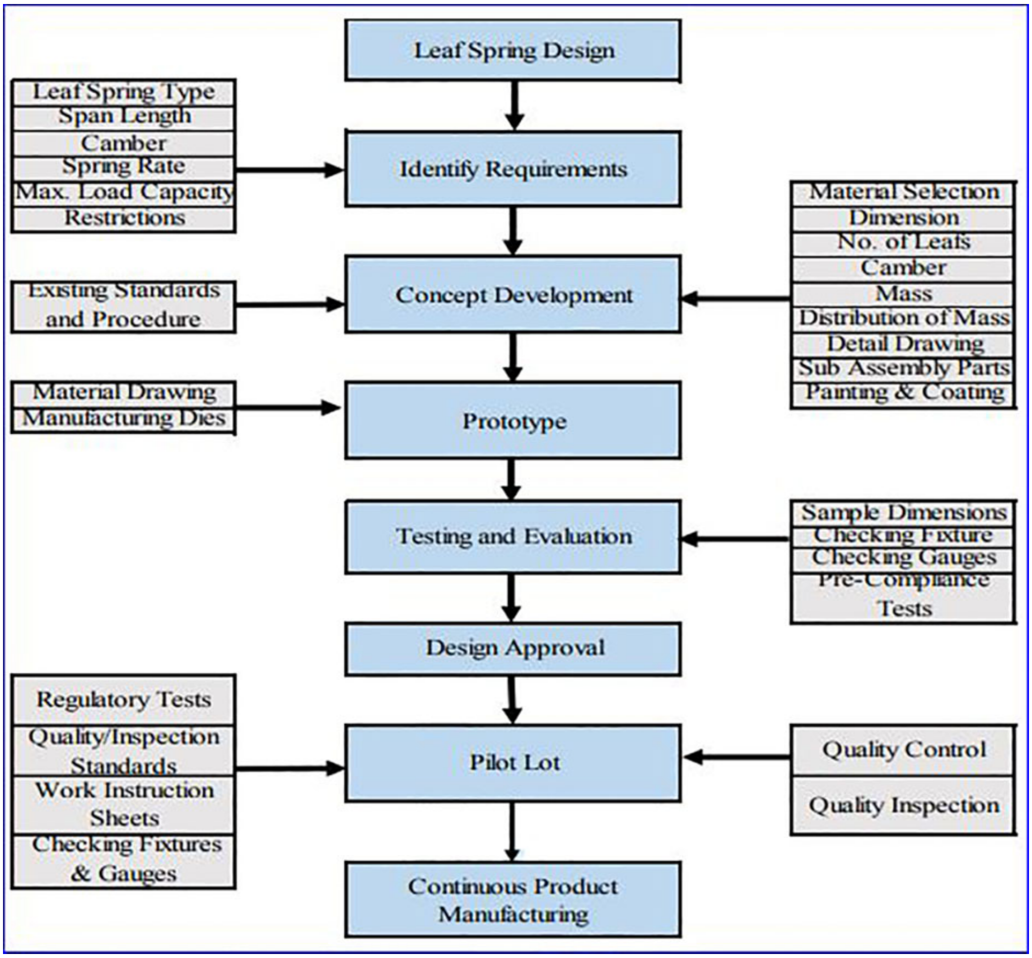

Figure 4. Leaf spring design steps.

Table 6. Design FMEA of leaf spring.

Sr.	Required function	Potential failure mode	Potential effect of failure	*S*	Cause of failure mode	*O*	Control method	*D*	RPN
1	Leaf dimensions	Thickness less than required	Spring constant decreases and unsatisfactory performance	8	Thickness not enough and thickness availability problem	2	Load deflection data, durability test, and on road test	3	48
		Span length more or less than required	Installation problem and unsatisfactory performance	8	Error in data collection and NG camber	6	Measuring tape, checking fixture, vehicle fitment test, and on road test	4	192
		Width less than required	Spring constant decreases and unsatisfactory performance	8	Space restrictions and width availability	1	Load deflection data and on road test	3	24
2	No. of leaf	No. of leaf less than required	Bending stress increases, spring constant decreases, and failure of leaf spring assembly	9	NG design	1	Durability test and stress analysis	2	18
3	Stresses in leaf and assembly	Non-uniform distribution of stress	Plastic deformation, failure of sub-assembly parts, and fatigue failure at less cycle	9	NG material, microstructure NG, NG hardness, NG design, and uneven stepping	1	Stress and strain analysis, material microstructure, and hardness test	2	18
4	Deflections and camber	NG deflection	Unsatisfactory performance and uncomfortable ride	8	Less thickness or width, NG material selection, NG material microstructure NG hardness	8	Load deflections data, hardness test, material microstructure test	3	192

(continued)

Table 6. (continued)

Sr.	Required function	Potential failure mode	Potential effect of failure	S	Cause of failure mode	O	Control method	D	RPN
		NG camber of assembly	NG clearance	5	NG setting load, NG free camber	5	Checking fixture, camber checking gauges of individual leaf	2	50
5	Mass and distribution of mass in leaf spring assembly	Improper distribution of mass	Unstable, unsatisfactory performance, and less durability	8	NG vehicle mass distribution on leaf spring assembly	1	Vehicle fitment tests and manual inspection	3	24
6	Load bearing capacity	Less bearing capacity than specified	Failure at user end	9	NG design	1	Load deflection data and specifying capacity on vehicle	2	18
7	Dimensions of main clip and U-clip	Bending, distortion, and fracture	Dismantling of leaf spring assembly	7	NG material, NG dimensions, and greater fitting force	1	Visual inspection	6	42
8	Bush specification	Bush pullout at less load	Failure at user end	9	Eye diameter greater than required	1	Bush pull out load test	2	18
		Distortion of bush during fitting	NG appearance	3	Eye diameter less than required	6	Visual inspection	6	108
9	Dimensions of center nut and bolt	Nut or bolt fracture	Dismantling of leaf spring assembly	8	Diameter not enough and NG material	5	Yield and tensile strength test	2	80
		Specifying less tightening torque	Dismantling of leaf spring assembly	8	Less tightening torque	1	Torque wrench	2	16
10	Eye rolling die	Die not making specified eye diameter or shape	Bush installation problem	8	NG dimensions or parameter, that is, diameter, force, temperature, finishing	8	Go/not go gauges	4	256
11	Tapper rolling die	Die not making specified tapper length or thickness	Stress concentration and fracture of tapered ends	5	NG tapper, finishing, or parameter, that is, force, temperature	5	Manual inspection	5	125
12	Edge cutting die	Die not making specified edge dimensions or shape	Stress concentration and fracture of edges	5	NG edge dimensions, finishing, or parameter, that is, force, temperature	4	Manual inspection	5	100
13	Paint type and thickness	Corrosion, peeling, and blistering	Reduced life and NG appearance	4	Less film thickness or NG parameters (pressure, temperature, distance, time)	1	Salt spray test, film thickness gauge	2	8

RPN: Risk Priority Number; FMEA: failure mode and effects analysis.

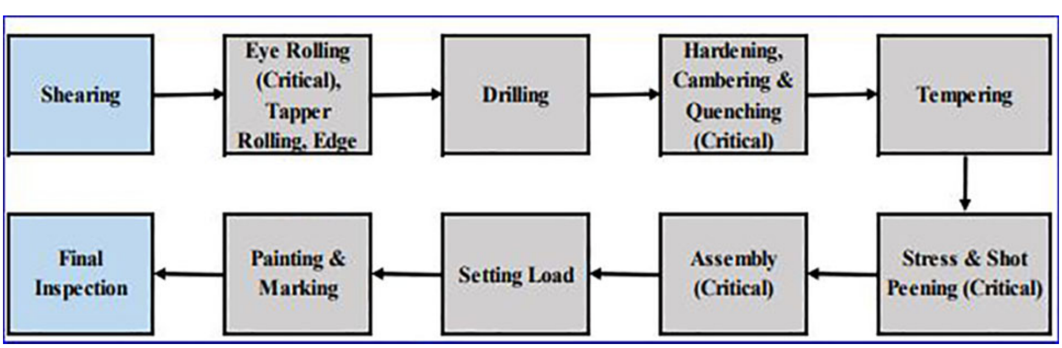

Figure 5. Leaf spring process flowchart.

shearing the leafs to required length. Then, first leaf is sent for eye rolling process in which leaf ends are first heated to red-hot temperature and then three dies make the required eye shape. Meanwhile, the other leafs are sent to tapper rolling and edge cutting. After drilling, the leafs are send to process of cambering in which leafs are first heated to red-hot temperature and then dies gave required shape to leafs which then dropped into quenching oil. Tempering and stress shot peeing are done to achieve required properties of leaf spring. Assembly of leafs and components is

Table 7. Rejections in manufacturing process of leaf springs.

Month	No. of leaf springs	Rejection	Less shearing length	Greater shearing length	NG eye size	Scaling of eye	NG tapper	Drill out of position	Distortion of sub-parts	NG dimension of sub-parts	NG camber of assembly	NG deflection	NG paint	Rust	NG final appearance
January 2019	374	16	3	0	0	0	2	1	0	1	2	0	0	2	5
February 2019	412	12	0	0	0	1	0	1	0	0	0	1	2	0	7
March 2019	360	9	1	0	2	2	0	1	0	0	1	0	0	0	2
April 2019	240	6	0	1	0	0	0	1	1	0	0	0	0	0	4
May 2019	440	26	4	0	0	2	0	3	0	0	2	0	3	0	11
June 2019	266	6	1	0	1	1	0	0	0	0	1	0	0	0	2
July 2019	336	7	0	0	0	4	0	0	0	0	0	0	1	0	2
August 2019	384	9	2	1	0	1	0	1	1	0	1	0	0	0	3
September 2019	240	8	0	0	1	0	1	2	0	0	0	0	1	0	2
October 2019	356	38	0	0	0	0	1	32	0	1	0	0	1	0	3
November 2019	118	3	1	0	0	1	0	0	0	0	1	0	0	0	0
December 2019	74	2	0	0	0	0	0	0	0	0	0	0	0	2	0
Total	3600	142	12	2	4	12	4	42	2	2	8	1	8	4	41

done with the help of hydraulic jacks. After all these processes, leaf spring assembly is set by applying required load. Now the assembly is painted and is ready to dispatch.

The functions involved in manufacturing process of leaf spring as shown in Figure 5 are then used in to develop FMEA. Potential failure modes are taken from historical defect data which include quality defect reports by customers, inhouse rejections, and inhouse repair orders as given in Table 7. Potential effects are derived by focusing on output of each step. All the ratings are developed from knowledge of process and then ratings are given according to severity, occurrence, and detectability tables. Potential causes of failure modes are derived from fishbone diagrams and detection are developed by analysis of measurement system. It is worth mentioning that occurrence and detection are relatively ranked within the scope of this FMEA. After collecting all the information PFMEA is started as given in Table 8.

Results and discussion

According to design and process FMEA, top 10 RPNs are shown in Figures 6 and 7, respectively.

Failure with RPN more than 250 are considered high priority failures according to Table 4 and actions are recommended for more reliable future design and manufacturing process. As shown in Figure 6, the highest RPN in designing of leaf spring is 256 for die which does not make specific eye shape or diameter. It can be controlled by designing dies of required dimensions then deciding the forging parameters.[23]

Highest RPNs in manufacturing process of leaf spring are of drilling out of position, less length for main leaf, and poor appearance of leaf spring. Center drill position can be controlled by stopper guiding the work piece, but it can easily change its position due to high number of cycles and vibrations. Periodic inspection after 1000 work pieces is recommended with proper drilling jigs that can hold the work piece and guide the tool. The second highest RPN is of less length for main leaf which can be controlled by periodic inspection of shearing machine and proper training of worker. The third highest RPN is of poor appearance of leaf spring assembly, because sub-assembly parts or paint can easily get damage due to miss handling. This problem can be solved by proper packing of sub-assembly parts. Work instruction sheets should also be updated for each manufacturing process mentioned above.

It is important to monitor or detect high severity failure modes in design and manufacturing of leaf spring. So, top failure modes according to the severity are shown in Figures 8 and 9.

Additionally, in designing of leaf spring highest occurring failures are improper deflection and poor eye shape, as shown in Figure 10. In development of leaf spring, it is important to achieve required deflection at given load. This process is iterative in which leafs of different width and thickness are used to achieve required deflection in

Table 8. Process FMEA of leaf spring.

Sr.	Required function	Potential failure mode	Potential effect of failure	*S*	Cause of failure mode	*O*	Control method	*D*	RPN
1	Material receiving	Material not as per standard	No production	8	Supplier failure, poor inspection	1	Supplier test certificates	3	24
		Thickness not as per standard	No production	8	Supplier failure, poor inspection	1	Supplier inspection sheet, incoming inspections	3	24
2	Material storage	Corrosion and rust due to high humidity	Poor strength and appearance of bar	5	High humidity storage, no proper ventilation	1	WIS, proper ventilation, material covering by plastic sheets	5	25
3	Shearing	Less length for main leaf	Span length will be less, fitting problem in vehicle	8	Stopper not guiding job, knife not sharp, tool mounted loosely, operator negligence	7	WIS, machine inspection and periodic maintenance, worker training	5	280
		Greater length for other leaf's	Increased stiffness, function problem	6	Stopper not guiding job, knife not sharp, tool mounted loosely, operator negligence	4	WIS, machine inspection and periodic maintenance, worker training	5	120
4	Eye rolling	NG eye size	Bush fitting problem, failure at user end	9	Die size NG, wrong inspection of dies	5	WIS, die inspection, go/no go gauges	4	180
		Scaling of eye	Poor appearance	4	NG parameters (temperature, time) problem	7	Visual inspection, parameter controlling, thermocouple	2	56
5	Half eye rolling	NG eye size, NG appearance	Assembly problem, function problem	6	NG parameters (temperature, time) problem	1	Visual inspection, gauge	5	30
6	Taper rolling	NG tapper dimension and appearance	Function problem	5	Die problem, parameters (temperature, time) problem	5	Visual inspection	6	150
7	Edge cutting	NG edge dimension appearance	Function problem	5	Die problem, parameters (temperature, time) problem	1	Visual inspection, gauge	5	25
8	Drilling	Drill out of position	Assembly problem, pad installation problem, fitting problem	7	Incorrect marking, operator negligence, stopper not guiding job	9	WIS, stopper guiding, periodic inspection	5	315
9	Hardening, quenching and tempering	Hardness greater or less than required	Failure at user end, function problem, no production	9	NG parameters (temperature, time problem, conveyor speed)	1	WIS, parameter inspection, hardness test, thermocouple	2	18
10	Stress peening and shot peening	Coverage less than 85%	Less durability	9	Less steel shots diameter, NG speed or coverage	1	WIS, visual inspection, Almen gauge test	4	36
		NG individual camber	Assembly problem, function problem	6	Bending jig problem	1	Free camber checking fixture, boundary checking	4	24
11	Sub-assembly parts inspection	Distortion/fracture of sub-assembly parts	Dismantling of leaf spring assembly	6	Supplier process failure, poor inspection	4	Visual inspection	6	144
		NG dimensions of assembly parts	Function problem	5	Supplier process failure, poor inspection	4	Manual inspection, supplier inspection sheets	5	100
12	Assembly	NG assembly of leaf's and sub-assembly parts	Function problem, no production, failure at user end	9	Personal error	1	WIS, visual inspection	6	54
13	Setting load	Assembly camber NG after setting load	Function problem, assembly problem	6	Applying less or greater presetting load, NG free cambers	6	WIS, free camber checking fixture, manual inspection	3	108
		NG deflection	Failure at user end, function problem	8	NG hardness, NG dimensions of leaf's	3	Hardness test, SDS	4	96
14	Fatigue/ durability testing	Less number of fatigue cycles	Failure at user end	8	NG design, NG material	1	Design review, mill test certificates	3	24
15	Painting and marking	NG paint, marking miss	Rust, NG appearance, less durability	4	Not proper coating	2	WIS, visual inspection, thickness tester	5	40
		Rust	Poor appearance	4	Not proper coating	7	Visual inspection	6	168
16	Final inspection	Dimension NG	Assembly problem, function problem	6	Poor inspection, less than 100% inspection	1	WIS, checking fixture, manual inspection	4	24
		Appearance NG	Function problem	5	Poor inspection, less than 100% inspection	9	Visual inspection	6	270

RPN: Risk Priority Number; FMEA: failure mode and effects analysis; WIS: Work Instruction Sheet; SDS: Sample Dimension Sheet.

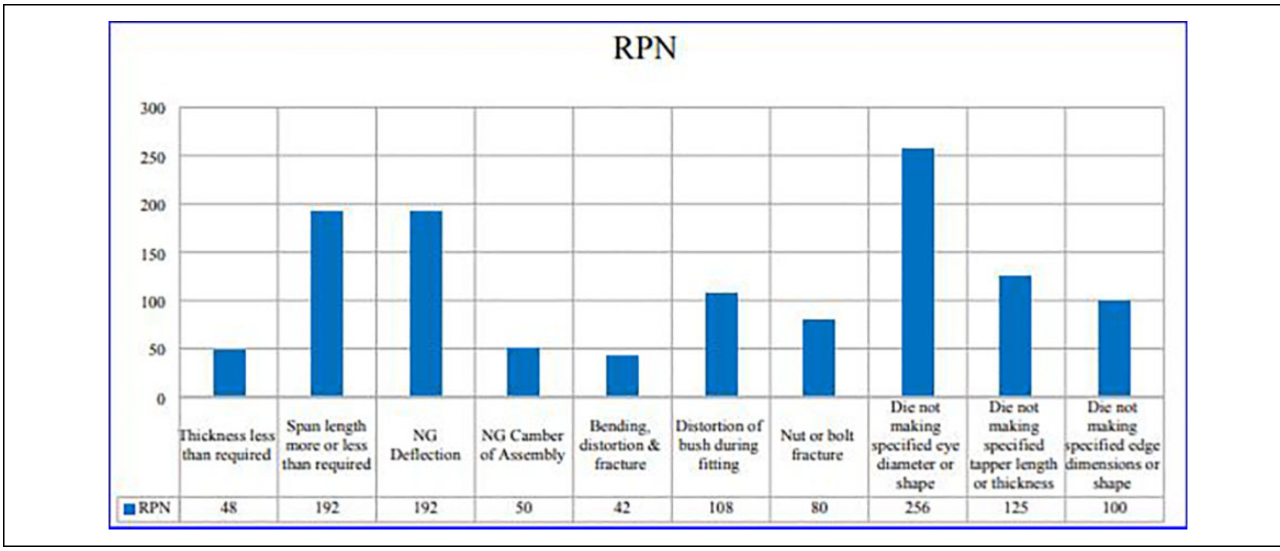

Figure 6. Top 10 RPNs from design FMEA. RPN: Risk Priority Number; FMEA: failure mode and effects analysis.

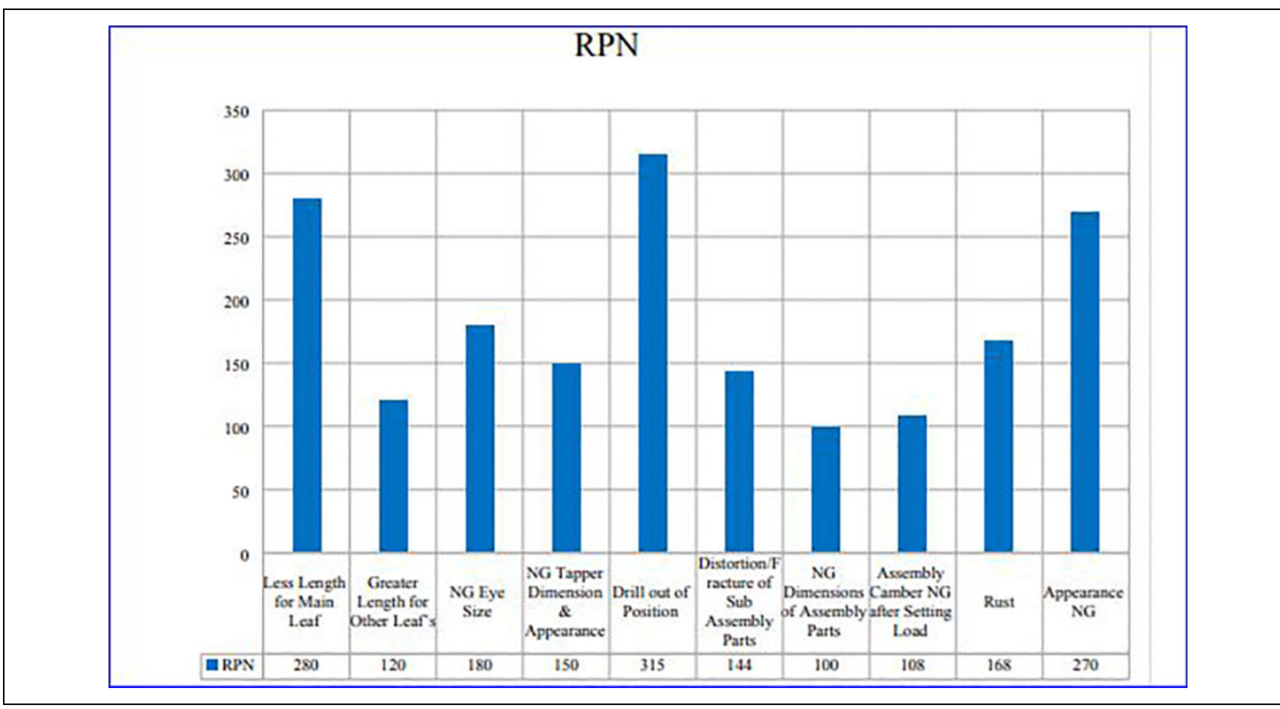

Figure 7. Top 10 RPNs from process FMEA. RPN: Risk Priority Number; FMEA: failure mode and effects analysis.

development phase. So, this results in higher rate of failure and poor performance of leaf spring assembly. The second highest occurring failure is in die which does not make required shape or diameter in start of development process. The flaws in design of dies are the main reasons for this failure and cause poor functioning and fitting problems of leaf spring assembly.

Similarly, highest occurring failure mode in manufacturing process of leaf spring occurs in drilling position and final appearance as shown in Figure 11. As mentioned above, drill bit can easily change its position due to high number of cycles and vibrations and cause fitting problem in vehicle. So, after 1000 work pieces a regular inspection is suggested with proper drilling jigs that can hold the work piece properly and guide the tool. Another high occurring failure is poor appearance of leaf spring assembly as sub-parts or paint can get easily damage due to miss handling. This problem can be solved by proper packing of sub-

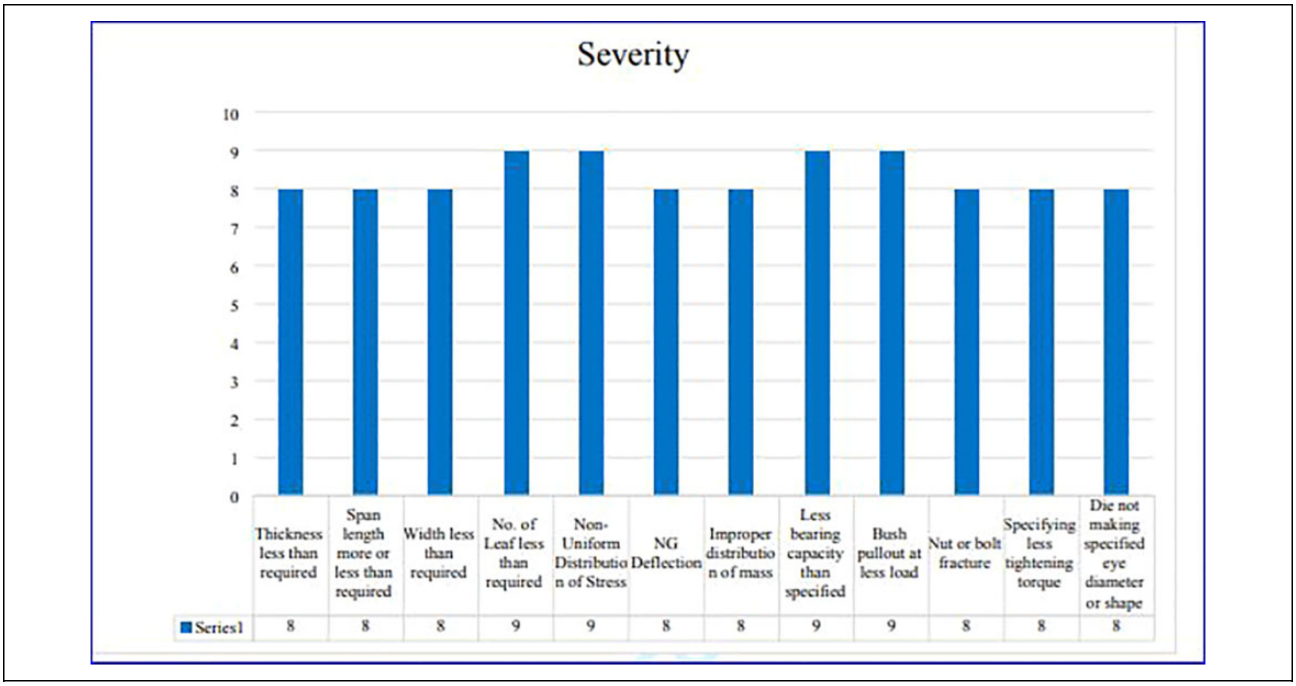

Figure 8. Top failure modes depending on severity in design of leaf spring.

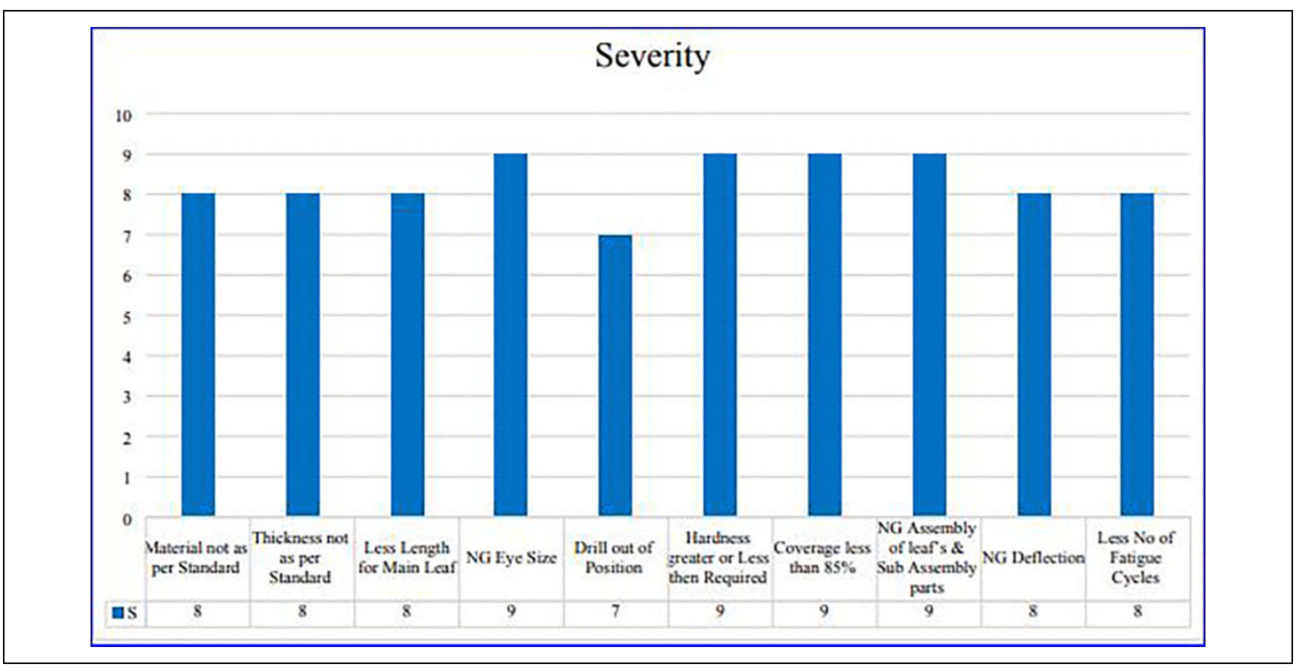

Figure 9. Top failure modes depending on severity in process of leaf spring.

assembly parts. These actions can be taken to reduce the rejection in manufacturing process of leaf spring.

Conclusion

Leaf spring is critical component for safety of passenger and vehicle. It is important to identify, control, and decrease potential failures in design and manufacturing process of leaf spring. In this research, FMEA is used as a tool to improve both automotive leaf spring design and manufacturing process. So, the improvement in design and manufacturing process is done by first predicting the possible failure modes and then eliminating those failures by applying recommended actions as discussed in the results section.

Top 10 highest RPNs of design are shown in Figure 3. The highest RPN in designing of leaf spring is for die that does not

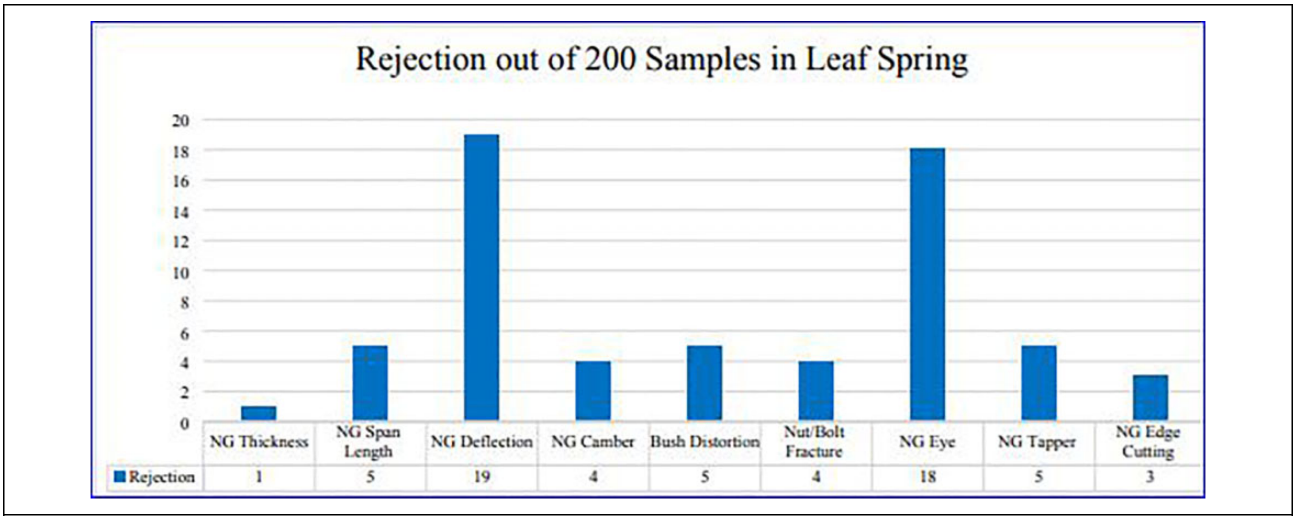

Figure 10. Rejection out of 200 samples in leaf spring development.

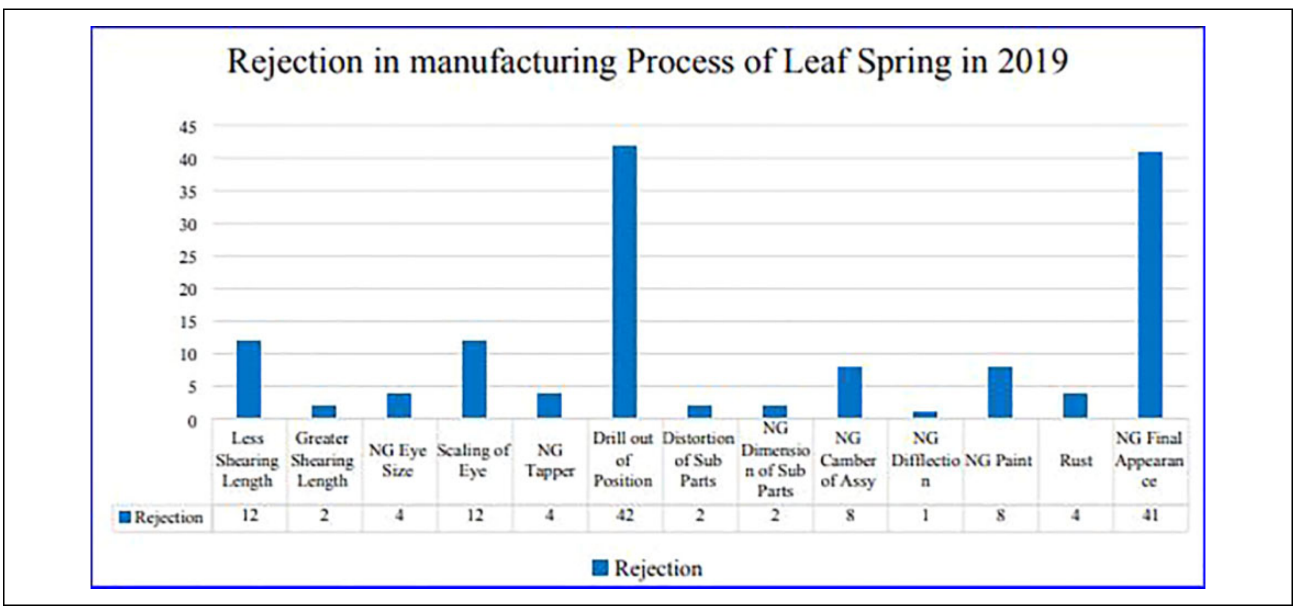

Figure 11. Rejection in manufacturing process of leaf spring in 2019.

make specific eye diameter or shape (RPN = 256), that is controlled by designing dies of required dimensions then deciding the forging parameters.[23] RPNs of center drill out of position, less length for main leaf, and poor appearance are 315, 280, and 270, respectively, that is shown in Figure 4. Center drill position can be controlled by drilling jigs and periodic inspection after 1000 work pieces. The less length for main leaf can be controlled by periodic inspection of shearing machine and proper training of worker. Poor appearance of leaf spring can be resolved by proper packing of sub-assembly parts. Work instruction sheets should also be updated for each manufacturing process according to recommended actions. Histograms of top failure mode depending upon severities and the occurrence of failures are shown in Figures 5 to 8. In the section of results, different solutions are recommended as positive approach by team of experts. FMEA provided improvements in terms of reduced rejection rate by ensuring high quality standards of leaf spring that is vision of industry. Furthermore, it will help organization to increase potential customer and market share.

Further scope for research

In this study, FMEA is implemented for 42 possible failures in designing and manufacturing process of leaf spring. It will help to increase the quality, reliability, and safety of leaf springs but there are some limitation in this method: (i) The multiplication of severity, occurrence, and detection rating make calculation of RPN questionable; (ii) although Delphi technique was used to calculate rating but there is still some uncertainty. The focus of future research will on fuzzy logic-based FMEA that can be used to resolve the above-mentioned shortcomings. Moreover, hybrid approach like FMEA combined with process capability analysis or GRA can also be used.

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References

1. Dutta S, Wankhede SB, Gadgil KV, et al. Failure mode effect analysis of analog alarm trip unit using simulation technique. In: Varde P, Prakash R, and Vinod G (eds) *Reliability, Safety and Hazard Assessment for Risk-Based Technologies*. Springer, Singapore: Lecture Notes in Mechanical Engineering, 2020, pp. 189–198.
2. Gundewar SK and Kane PV. Fuzzy FMEA analysis of induction motor and overview of diagnostic techniques to reduce risk of failure. In: Varde P, Prakash R, and Vinod G (eds) *Reliability, Safety and Hazard Assessment for Risk-Based Technologies*. Springer, Singapore: Lecture Notes in Mechanical Engineering, 2020, pp. 927–939.
3. Bakhshi R, Sandborn P, and Lillie E. Assessing the value of corrosion mitigation in electronic systems using cost-based FMEA—Tin Whisker Mitigation. In: Vachtsevanos G, Natarajan K, Rajamani R, and Sandborn P (eds) *Corrosion Processes*. Vol. 13. Springer, Cham: Structural Integrity, 2020, pp. 313–339.
4. Nataraj M and Thillikkani S. Failure analysis of leaf spring suspension system for heavy load truck vehicle. *Int J Heavy Vehicle Syst* 2020; 27(1–2): 1–17.
5. Koomsap P and Charoenchokdilok T. Improving risk assessment for customer-oriented FMEA. *Total Qual Manag Bus Excel* 2018; 29(13–14): 1563–1579.
6. Rezaee MJ, Yousefi S, Valipour M, et al. Risk analysis of sequential processes in food industry integrating multi-stage fuzzy cognitive map and process failure mode and effects analysis. *Comput Indust Eng* 2018; 123: 325–337.
7. Kim KO and Zuo MJ. General model for the risk priority number in failure mode and effects analysis. *Reliabil Eng Syst Safet* 2018; 169: 321–329.
8. Peeters J, Basten RJ, and Tinga T. Improving failure analysis efficiency by combining FTA and FMEA in a recursive manner. *Reliabil Eng syst safet* 2018. 172: 36–44.
9. Spreafico C, Russo D, and Rizzi C. A state-of-the-art review of FMEA/FMECA including patents. *Comput Sci Rev* 2017; 25: 19–28.
10. Sutrisno A, Gunawan I, Vanany I, et al. An improved modified FMEA model for prioritization of lean waste risk. *Int J Lean Six Sigma* 2018; 11(2): 233–253.
11. Baynal K, Sarı T, and Akpınar B. Risk management in automotive manufacturing process based on FMEA and grey relational analysis: a case study. *Adv Prod Eng Manag* 2018; 13(1): 69–80.
12. Liu H, Deng X, and Jiang W. Risk evaluation in failure mode and effects analysis using fuzzy measure and fuzzy integral. *Symmetry* 2017; 9(8): 162.
13. Fragoudakis R, Savaidis G, and Michailidis N. Optimizing the development and manufacturing of 56SiCr7 leaf springs. *Int J Fatig* 2017; 103: 168–175.
14. Fonte M, et al. Failure mode analysis of two diesel engine crankshafts. *Proced Struct Integ* 2016; 1: 313–318.
15. Lijesh K, Muzakkir S, and Hirani H, Failure mode and effect analysis of passive magnetic bearing. *Eng Fail Analy* 2016; 62: 1–20.
16. Sellappan N and Palanikumar K. Modified prioritization methodology for risk priority number in failure mode and effects analysis. *Int J Appl Sci Technol* 2013; 3(4): 27–36.
17. Kolich M. Using failure mode and effects analysis to design a comfortable automotive driver seat. *Appl Ergonom* 2014; 45(4): 1087–1096.
18. Feili HR, Akar N, Lotfizadeh H, et al. Risk analysis of geothermal power plants using failure modes and effects analysis (FMEA) technique. *Energ Conver Manag* 2013; 72: 69–76.
19. Sellappan N, Nagarajan D, and Palanikumar K. Evaluation of risk priority number (RPN) in design failure modes and effects analysis (DFMEA) using factor analysis. *Int J Appl Eng Res* 2015; 10(14): 34194–34198.
20. Vinodh S and Santhosh D. Application of FMEA to an automotive leaf spring manufacturing organization. *TQM J* 2012; 24(3): 260–274.
21. Xiao N, Huanga H-Z, Li Y, et al. Multiple failure modes analysis and weighted risk priority number evaluation in FMEA. *Eng Fail Anal* 2011; 18(4): 1162–1170.
22. Totten GE, Xie L, and Funatani K. *Handbook of mechanical alloy design*, vol. 164. Boca Raton, FL: CRC Press, 2003.
23. Altan T, Ngaile G, and Shen G. *Cold and hot forging: fundamentals and applications*, vol. 1. Cleveland: ASM International, 2004.