STEEL DEVELOPMENT FOR U-BOLTS USED IN LEAF SPRINGS SYSTEMS USING COLD-FORMING PROCESS

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Abstract. *In this present work the steel and the production process were developed, in order to produce U-Bolts to light, medium and heavy commercial vehicles, without any heat treatment, such as heating and tempering. Thus, this research uses five types of steel with different additions of chrome, nickel and silicon to allow the cold forming processing of the U-Bolts, assuring the mechanical properties required, as, minimum ultimate strength (900 MPa), minimum yield stress (720 MPa), minimum elongation (10%) and hardness (24-32 HRC). The developed steel exhibited a microstructure composed by perlite and ferrite, with the perlite grain size (ASTM) in the range of 9 to 11, by aluminum and vanadium additions that acted as grain size refiners. The evaluation of the mechanical properties was made according to ASTM A-370 and the samples tested in a dynamic system – MTS 810. The microstructure and fractography analyses of the steel after cold forming were made using optical and scanning electronic microscopes. Finally, to evaluate the performance of the steel and the production process, fatigue tests were carried out under a load control (tensile-tensile), R = 0,1 and f = 30Hz. Weibull statistic method was used for the analysis of the fatigue results and the steel with chrome addiction (0,21%), Alloy 2, presented the best fatigue performance.*

Keywords*: U-bolts; Low steel; Cold forming; Leaf spring.*

1. INTRODUCTION

Over the last decades, there has been a growing interest from the automotive industry in reducing costs of productive processes and aggregating new technologies in the components of vehicles. This way, new materials and processes are constantly in development in an attempt to improve the mechanical properties of these components. The addition of alloy elements in the steels associated to ambitious production processes is proving to be a quite viable way for obtaining the required results.

In the same way, this tendency has also been observed in the production of suspension systems of automotives vehicles, which are constituted of sheets that are kept together by the use of bolts, which forms what is called spring steels.

The use of bolts has the objective of maintaining the spring steel attached to the axis of the vehicle, forming a solid group of the three components of the suspension: the axis, the spring steel and the supporting plate. It is known that some components are combined in the suspension of the vehicles, forming a complex union with the bolt. Each one of these components has its effect on the performance of union of this system with the bolt. The bolts and other components act with the forces of action and reaction and always in the opposite direction than that of the springs of the suspension; and the bolts themselves support all the tension forces. One of the functions of the bolts in the system is to absorb the discharges tensions generated by the suspension in work cycles. The united suspension is dynamically loaded and a minimum force of turning moment should be maintained or the bolt will fail in fatigue [Baggerly, 1994].

The bolts can be mounted with the round part in contact with the piece of setting of the spring or mounted with the round part in contact with the axis, according to what is shown in Figure 1. The bolts are basically divided in two geometric forms that are usually called square format (Figure 2(a)) and round format (Figure 2(b)). In Figure 1, it can be observed that the system is submitted to a force (F) originated from the maximum stress to which the spring is submitted during work [CMP, 2002]. The bolts should support the maximum stress.

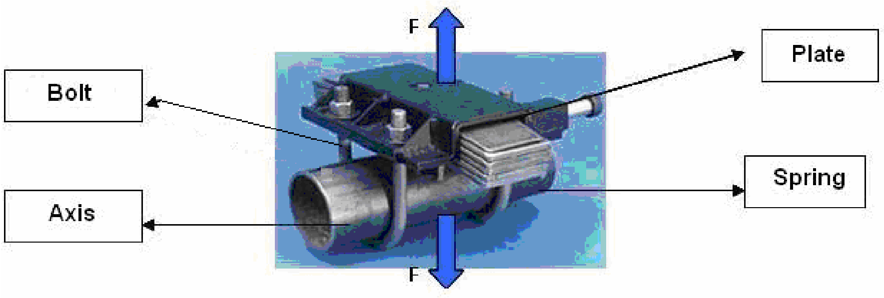
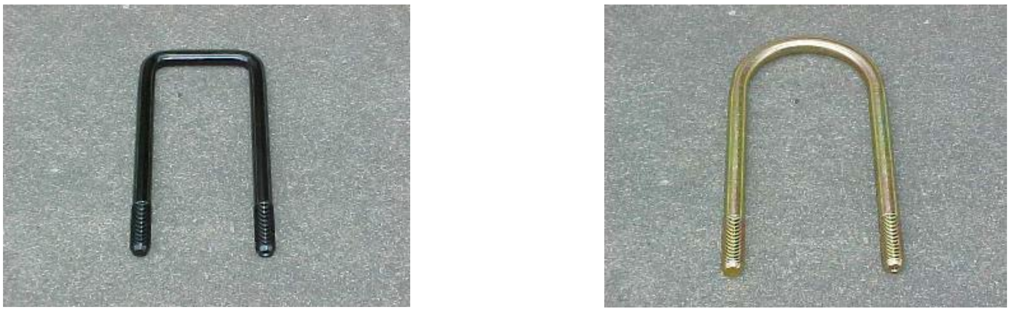


Figure 1. Outline showing the system of fixation of the spring steel and the direction of the forces to which it is submitted [CMP, 2002].



(a) (b)

Figure 2. Formats of the bolts used in suspensions of vehicles: (a) square and (b) round.

Bolts are usually manufactured at high temperatures, from the use of steel SAE 4140 and they should be quenched and tempered in order to obtain a microstructure which is mainly composed of tempered martensite to ensure the level of mechanical resistance that is necessary for the expected lifespan of the component. The flow diagram in Figure 3 presents the productive process of the bolt of steel SAE 4140, which is a complex one, in which the bolts are submitted to a heating of about 850ºC for the forming of the fold (U) and soon after they are further heated to 900ºC, quenched in oil and tempered at 460ºC.

However, this manufacture process creates some problems that affect the performance of the bolt during use, as decarburizing in the screw threads, cracks in the heat treatment and problems as products of transformation of undesirable phases that end up weakening the component. These problems, when combined, end up directly influencing the required mechanical properties and in the life in fatigue of the final product.

Over the last decades the hot forming process has, continually, improved. However the use of technology in this process has not entirely eliminated the defects, which eventually are created during manufacture. Several improvements in the steel mills were implemented, such as: the reduction of the decarburizing in the raw materials obtained by the process of continuous ingot casting, the control of the atmosphere in the furnaces by controlling the internal oxygen, the change of the means of combustion from oil to for gas, the improvement in the control of the temperature, the implementation of the automatic control in the lamination train to locate defects in the bars during this process, etc.

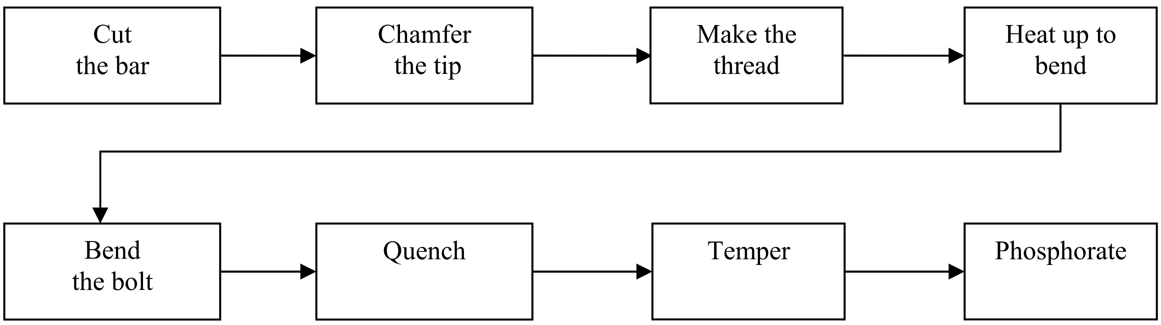


Figure 3. Flow chart of bolt production in the hot forming process.

The manufacturers of current bolts also implemented improvements in the production process, such as: controlling the atmosphere of the heating furnaces, controlling the temperature of the quenching oil, using long tempering furnaces in order to obtain more homogeneous hardness, among others. However, this production model may still generate defects which are created during the manufacture process.

The cold forming process is one of the production processes that has received a great deal of attention as a method for the production of automotive components, in that it mainly aims an increase in resistance and this way it avoids the stages of heat treatments that, besides being more expensive due to high consumption of gas and electric power, also requires a more severe control of the furnace temperatures and exposure time. When these parameters fail, they generate a decrease in the quality of these components, as, for instance, for the occurrence of microcracks, variation of hardness and decarburizing.

2. MATERIALS AND METHODS

2.1. Materials

The steel SAE 4140, which was used as reference for this project, is a steel-carbon with addition of manganese. Table 1 presents the chemical compositions of the studied steels.

Table 1. Chemical compositions used for the steel SAE 4140 and the alloys tested (% weight).

Alloys	SAE 4140	1	2	3
C	0,47 – 0,55	0,55	0,48	0,36
Si	–	0,26	0,26	0,64
Mn	1,2 – 1,5	1,13	1,18	1,33
P	0,04 (máx)	0,017	0,016	0,014
S	0,05 (máx)	0,013	0,023	0,057
Cr	–	0,35	0,21	0,13
Ni	–	0,02	0,10	0,15
Cu	–	0,02	0,13	0,18
Al	–	0,014	0,024	0,025
V	–	0,002	0,080	0,114
Mo	–	–	0,04	0,02
Nb	–	0,001	–	–
Ti	–	0,005	–	–
B	–	0,0004	–	–

From consulting the literature, some chemical elements were selected for the compositions of the studied alloys:

a) Silicon: a range of 0,24% to 0,64% in weight was established once the Si constitutes an impurity in the steels but does not have a great influence in its properties. In order to verify its influence, an alloy with minimum level and other with the maximum level of this element was prepared.

b) Chrome: it was added in the Alloys 1, 2 and 3 to increase the hardness and the yield point, and in Alloy 3 it was added in lower percentage (0,13% in weight), due to the percentage of nickel and silicon that were already high in Alloys 1 and 2.

c) Nickel: in Alloy 1 the addition of nickel was discreet due to the fact that the percentages of carbon and chrome were higher. In Alloys 2 and 3 nickel was added in order to increase the tensile strength, the yield point, the hardness and the tenacity.

d) Aluminum: it was added to combine with the vanadium and together they contribute to obtain a refined size of grain, which also contributes to improve the mechanical resistance and the fatigue, as well as in the operation of bending the bolt.

e) Vanadium: it was especially added in Alloy 3 in levels of 0,114% in weight to obtain an ASTM grain size of between 9 to 11, as well as increase the tensile strength without reducing the ductility and increase the resistance in fatigue.

Bolts were manufactured with the U format. The thread (M12x1,25) was made by the process of plastic deformation (rolling). Figure 4 presents the geometry and the dimensions of the manufactured bolts.

2.2. Cold forming

Due to the fact that the new product should not be quenched and tempered, the chemical composition would not be enough to ensure the mechanical properties and resistance to fatigue of the bolt. Therefore, the new steel should be deformed at cold temperatures to increase its mechanical resistance. This deformation will still be added to the forming deformation of the screw threads. Table 2 presents the start and end gauges, as well as the real deformation obtained from the drawing process for the level of true deformation selected for this work.

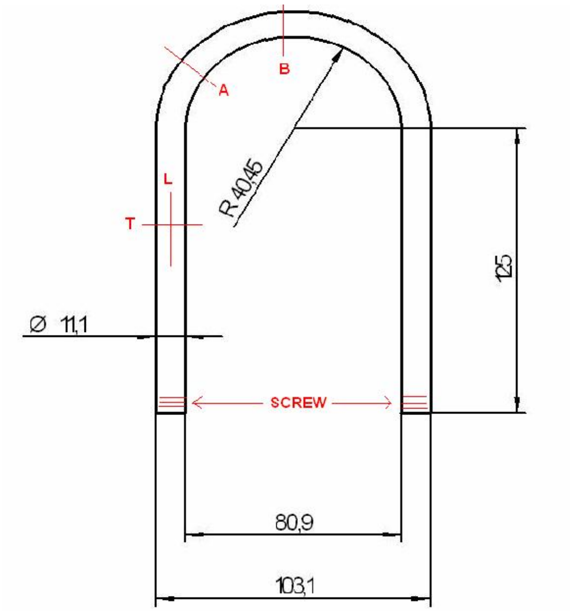


Figure 4. Geometry and dimensions of the U-bolts. The writings in red refer to the indications of the positions where the samples were removed for the metallographic analysis and measured as for the grain size ASTM.

Table 2. Levels of true deformation taxes to the steel alloys.

Alloys	Start gauge [mm]	Final Gauge [mm]	ε_T [%]
1	14,30	11,09	22,44
2	12,70	11,06	24,16
3	12,70	11,06	24,16

2.3. Microstucturals analysis

The aim of this analysis was to verify the microstuctural composition, grain size, decarburizing and discontinuities present in the steel. The microstructural analysis was carried out in the points indicated in Figure 4 (in red), that is, in the longitudinal and transversal directions of the long stem, in the transversal sections A and B, and in the root of the thread. In all the cases the analyses were carried out in the surface and in the center of the bar.

The test samples were removed from the bolts in study, and afterwards, they were embedded in bakelite, sanded in sandpapers of granulometries 300, 400, 500, 600, 800 and 1200. Following this, they were polished in chrome oxide and in diamond paste. After polishing they were attacked with Nital 2% and observed in optic microscope. For the evaluation of the grain size, a Buehler Omnimet Enterprise image analyzer was used.

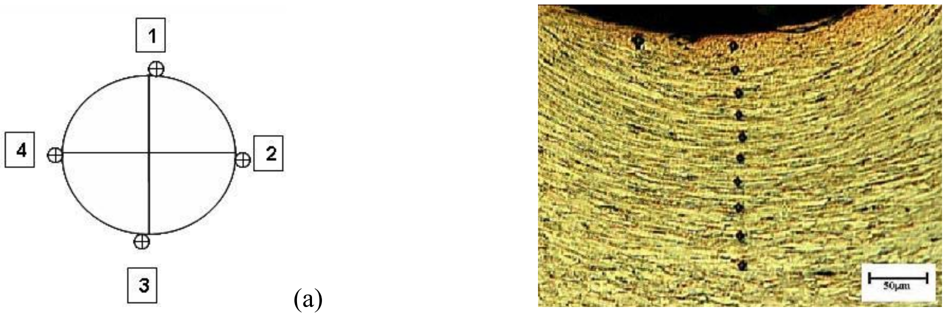
2.4. Hardness tests

Measures of hardness were realized in the bar after drawing and rolling for making the threads. The hardness measures for evaluation of the strengthening for cold working were accomplished in the Rockwell C scale, with load of 150,0 kgf, and these measures were taken in the surface with diamond indenter, totaling four measures per sample, as shown in the Figure 5(a). For the evaluation of the cold working, caused by the rolling of the threads, measures of hardness Vickers were realized, taken from 10 different points the profile of the screw thread toward the nucleus of the bar (Figure 5(b)), using an indenter of pyramidal base of diamond.

2.5. Tension tests

The samples were prepared for the selection of the level of cold working to be applied during the process of drawing of the bars. These tests carried out according to the ASTM E8M norm [ASTM E 8M-01, 2001], with displacement speed of the crossbeam of 1,0 mm/min. The used equipment was a test machine EMIC DL10000. Cylindrical samples whose sizes are presented in the Figure 6 were used. For each material and deformation condition three samples were tested.

Through these tests, the curves S-ε for each alloy were drawn, obtaining, in that way, the properties of percentual elongation, yield point (MPa) and tensile strength (MPa).



(a) (b)

Figure 5. Outline showing the positions of measurement of hardness: (a) in the bar of steel and (b) in the screw thread.

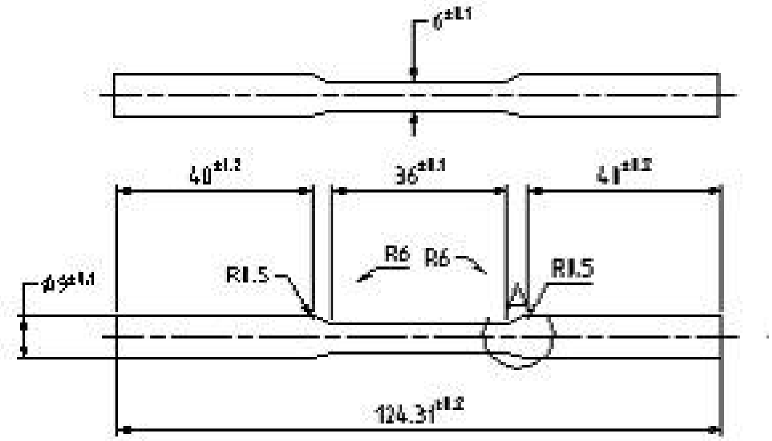


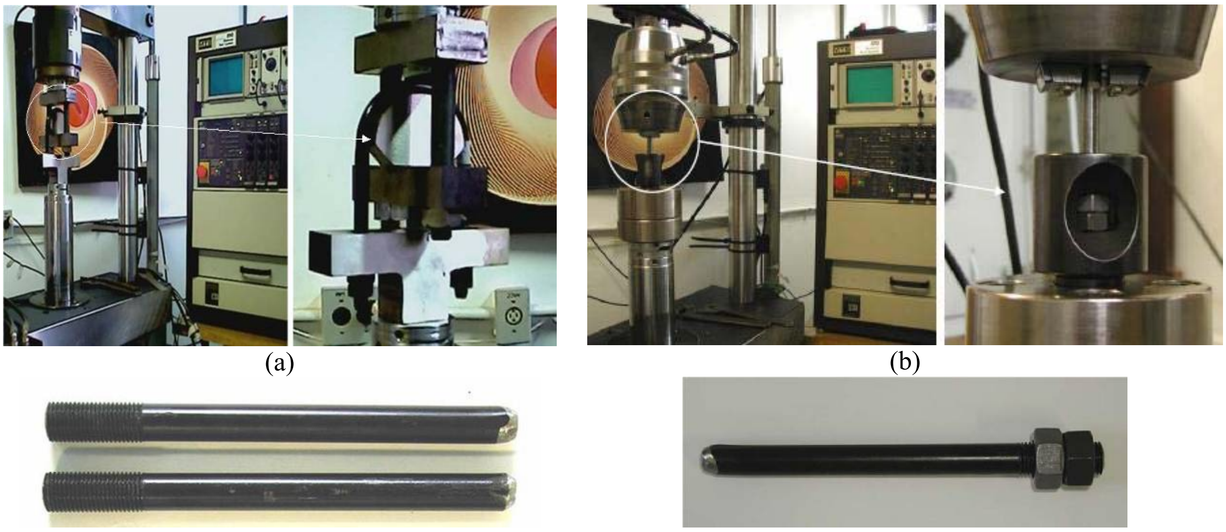
Figure 6. Geometry and sizes of the sample tension [ASTM E 8M-01, 2001].

2.6. Fatigue tests

The fatigue tests were carried out with the aim of characterizing the material and the process of production of the bolts as for the exposure to cyclical loading, which happens in vehicles. The used equipment was a test servo-hydraulic system MTS 810 with load cell of 100 kN. The conditions tests were: control of stress amplitude axially imposed to the sample; load ratio of 0,1 (tension-tension); room temperature; senoidal wave; frequency of 30 Hz.

Initially, the bolts in their final form were tested. For that, it was necessary to make a system of claws presented in the Figure 7(a) for support and fixation. However, with the use of this system, there were problems in the alignment of the bolt and fractures of the screw supports, which made this method inappropriate for this test. Therefore, test samples, which were obtained directly from the bolts (each " leg of the bolt " constituted a sample) were used in the test, as it can be seen in the Figure 7(c). For the test, a screw test support and a hydraulic claw were used. The flat part of the sample was attached to the hydraulic claw while the threaded part was place, with the use of nuts, in the support for screw test. Figure 7(d) shows a sample with the two nuts (nut and against-nut). Figure 7(b) shows a sample assembled in the machine and ready for the realization of the test.

For the analysis of the results, the methodology of "accumulated probability of fail (Weibull)" was used. The criterion used to evaluate the performance was the life B10 and B90 where B10 represents that 10% of the samples can fracture below the specified minimum life and B90 it represents that 90% of the samples can have a superior life to the specified. In this analysis, a minimum of 8 samples of each material were submitted to the loading in fatigue under the same tension range constant previously determined based on the mechanical properties of the material. Usually, fail due to complete rupture of the samples happens for a number of nearly 10^5. This method provides a percentage of replication of 90%. The results of this methodology are presented as curves of probability of failure versus life in fatigue (Nf), where Nf is the number of cycles necessary for the failure of the sample per complete fracture. In these analyses, the two parameters (m, θ) statistical model of Weibull will be used, especially developed for the analysis of failures.



(a) (b)

(c) (d)

Figure 7. Fatigue test: (a) and (b) assembling of the equipment; (c) sample removed of the "legs" of the bolts; and (d) sample ready to be tested.

3. Results and Discussions

3.1. Actual value of the stress concentration factor at the thread root (K_t and K_f)

For the calculation of the maximum stress used during the test, it is necessary to consider the fatigue stress concentration factor, (K_f) in the screw thread of the bolt. This factor can be obtained from the literature [Peterson, 1974] and it depends on the characteristics of the thread, (step, ray and depth) and of the material type.

For the thread in question, M12 x 1,25, where b = 1,25 mm and t = 0,767 mm (values taken from the norm ASME B1.13M-2001). For b/t = 1,63, be obtained λ=0,5 (Figure 10). Therefore:

$$K_t = 1 + 2.\left(\frac{0{,}3835}{0{,}180}\right)^{0{,}5} \cong 3{,}92 \text{ MPa}\cdot\sqrt{\text{m}} \quad (1)$$

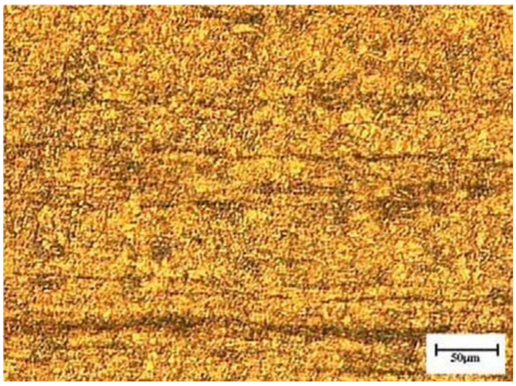
For the materials used in this work, the average value of the a will be of approximately 0,095 mm. The parameter r is minimum ray in the root of the thread, which is of 0,180 mm in this work (values taken from the norm ASME B1.13M-2001). Therefore:

$$K_f = 1 + \frac{3{,}92 - 1}{\left(1 + \frac{0{,}095}{0{,}180}\right)} \cong 2{,}91 \text{ MPa}\cdot\sqrt{\text{m}} \quad (2)$$

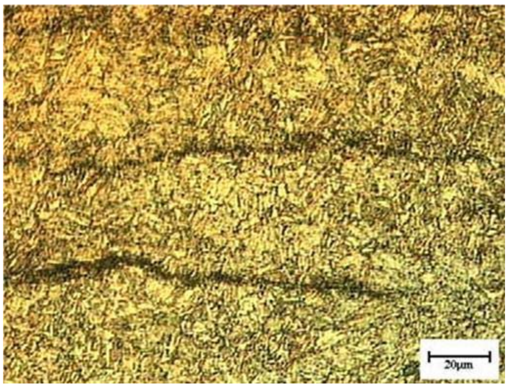
The calculations of the tension in the thread concentration factors showed that the values of K_f are approximately 25% smaller than the values of K_t in the root of the thread.

3.2. Microstructural analyses, hardness and tension

The Figures 8, 9, 10 and 11 present the microstructural characterization of the steel SAE 4140 (quenched and tempered) and of the Alloys 1, 2 and 3, respectively.



(a)



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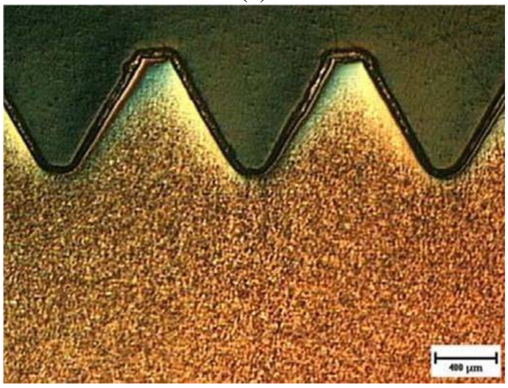
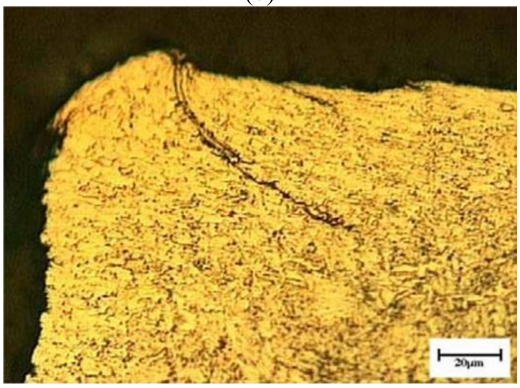
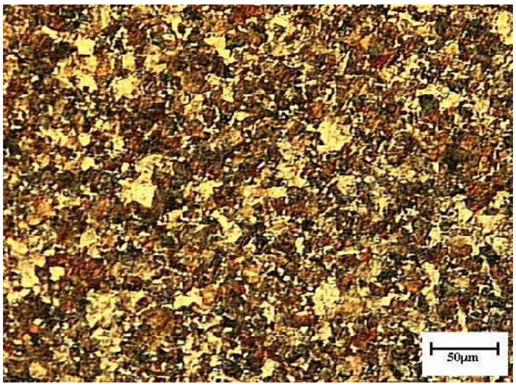


(c)

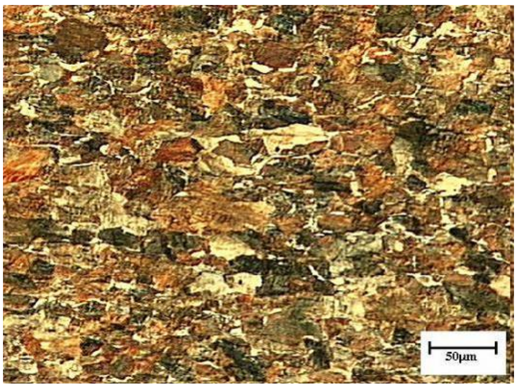


(d)

Figure 8. Microstructure of the steel SAE 4140 after quenching and tempering, observed in the traverse direction: (a) structure composed of tempered martensite and (b) detail of (a) showing the segregation lines. (c) General aspect of the profile of the thread; (d) detail of the profile of the thread showing the existence of microcracks appeared during the quenching.



(a)



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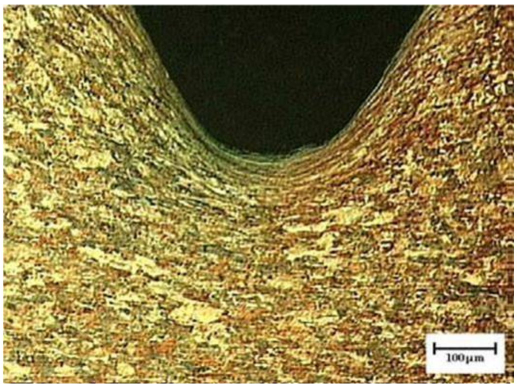
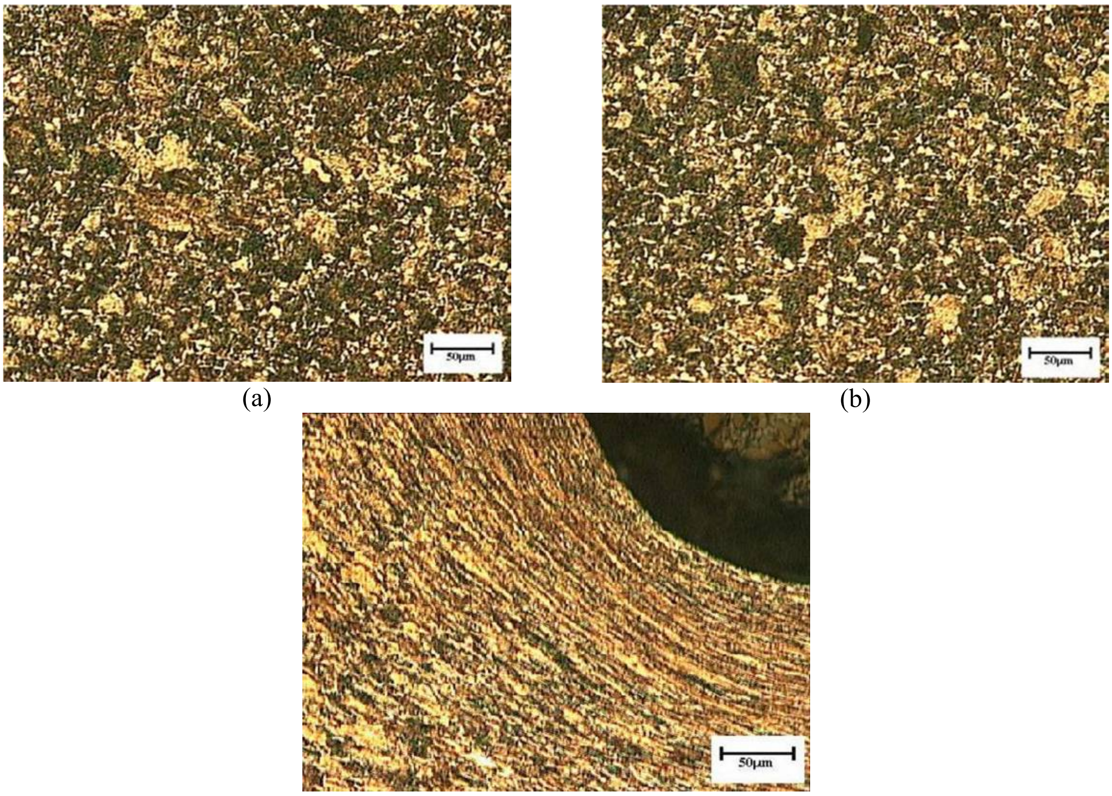


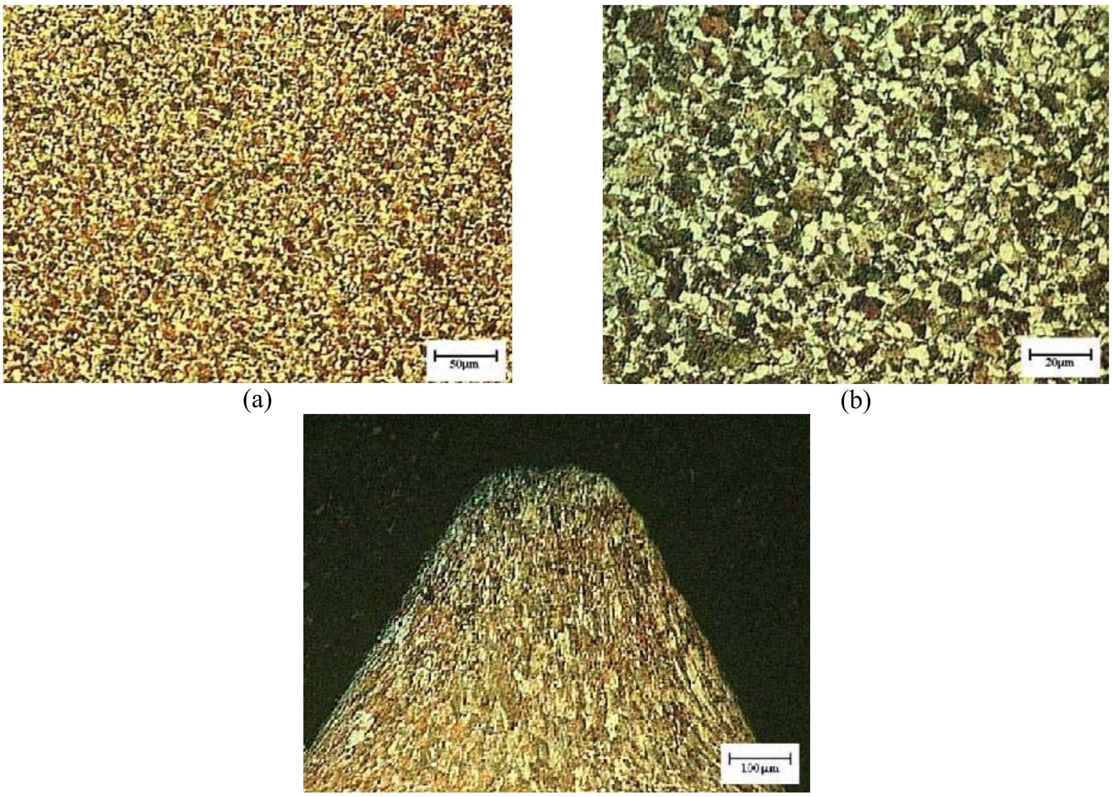
(c)

Figure 9. Microstructures of the Alloy 1: (a) transversal direction and (b) longitudinal direction. (c) Aspect of the profile of the thread.



(a) (b) (c)

Figure 10. Microstructures of the Alloy 2: (a) transversal direction and (b) longitudinal direction. (c) Aspect of the profile of the thread.



(a) (b) (c)

Figure 11. Microstructures of the Alloy 3: (a) transversal direction and (b) longitudinal direction. (c) Aspect of the profile of the thread.

As previously mentioned, the current bolts are manufactured by the process of hot production, that is, quenched and tempered. Thus, for comparison reasons, microstructural analysis of the SAE 4140steel used in the production of the bolts was realized. The final microstructure is of tempered martensite, Figure 8(a). Some segregation lines (Figure 8(b)) and microcracks in the screw threads were still observed (Figure 8(d)). It was observed that in the profile of the thread a superficial layer of treatment called duo-chrome-plated layer was present. Many times the aspect of this layer induces to the interpretation of a decarburized layer. The detail (Figure 8(c)) shows that decarburizing was not present. However, several microcracks and emptiness appear in Figure 8(d).

Similar to what was observed for Alloy 1, the structure of Alloy 2 is also constituted of perlite grains and ferrite (clear phase), as Figures 9 and 10 show. As it can be observed in Figure 10, the process of rolling of the thread has caused a great amount of superficial plastic deformation in it. The plastic deformation in Alloy 3 was observed in the area of the thread (Figure 11(c)), where the cold rolling operation was realized.

Table 3. Values of hardness obtained in the bar surface and in the root of screw thread.

Measure points	**SAE 4140**	**Alloy 1**	**Alloy 2**	**Alloy 3**
Bar surface [HRC]				
Mean (4 points)	27,5	28,5	22,4	32,8
Root of screw thread [HRC]				
1	29,9	44,5	41,2	50,4
2	26,6	43,9	42,0	50,0
3	28,1	43,6	46,0	48,6
4	27,9	43,0	46,0	49,6
5	26,1	42,6	44,9	45,3
6	26,4	42,1	45,6	46,4
7	26,9	41,0	44,6	42,0
8	26,7	41,0	42,0	46,4
9	28,1	41,5	43,5	39,4
10	27,1	-	-	39,1

From these results, it can be observed that the largest level of superficial hardness was obtained for the bolts manufactured starting from the Alloy 3 (32,8 HRC), followed by the bolts of the Alloys 1 and SAE 4140 (28 HRC) and of the Alloy 2 (22,4 HRC). In the root of the screw thread the same tendency of values of hardness can be observed. However, as expected, the highest values of hardness were obtained at the root of the thread, due to a larger located plastic deformation caused by the rolling process of the thread. In Table 4 the results of all the tests for each alloy are shown.

Table 4. Mechanical and microstructurals properties of each alloy used in this work.

Properties	**Objectives**	**SAE 4140**	**Alloy 1**	**Alloy 2**	**Alloy 3**
Tensile strength [MPa]	900 (min)	1052,7 ± 0,9	1054,6 ± 1,2	1053,1 ± 0,5	1053,4 ± 0,9
Yield point [MPa]	720 (min)	950,5 ± 1,2	772,3 ± 0,9	839,1 ± 1,1	886,5 ± 1,0
Elongation[%]	10 (min)	12,1 ± 0,3	11,6 ± 0,2	13,2 ± 0,4	9,3 ± 0,3
Surface hardness [HRC]	24 – 32	27,6 ± 0,7	28,5 ± 0,3	22,3 ± 0,4	32,8 ± 0,4
Microstruture	Fine perlite	Tempered martensite	Fine perlite	Fine perlite	Fine perlite
Grain size (ASTM)	8 or more fine	6 a 7	7 a 8	9 a 11	8 a 10

The microstructures of the Alloys 1, 2 and 3 are composed of grains of fine perlite surrounded by ferrite. The difference is in the proportion among the phases in each type of steel. The material SAE 4140 presented a different structure, that is, tempered martensite for suffering a heat treatment of quenching and tempering. Numerically, the Alloy 3 was the one that showed better results of mechanical properties, especially in tensile strength, which should be better for the operation of the bolt, once the bolt works in alternate tension-tension type loading. However, it was also observed that the hardness of the Alloy 3 was the highest, which could affect the cold lamination of the thread and generate some tension concentration in the profile of the thread. The chemical elements Al and V of the Alloy 2 contributed to the refinement of the grain size (ASTM no. 9 to 11).

3.3. Fatigue tests

Table 5 presents the results of the fatigue life for the bolts used in this work, comparing your results with the one obtained for the SAE 4140 steel quenched and tempered. The graphs of probability of failure versus fatigue life (Nf) were obtained using a program that calculates the distribution of Weibull for two parameters.

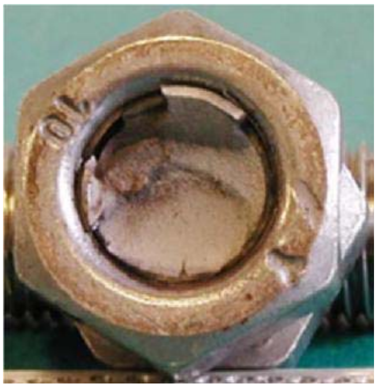
Table 5. Results in fatigue life of the bolts used in this work.

	Materials			
Samples	**SAE 4140**	**Alloy 1**	**Alloy 2**	**Alloy 3**
1	----	$1,10 \cdot 10^6$	$9,60 \cdot 10^5$	$5,83 \cdot 10^5$
2	$3,80 \cdot 10^5$	$6,06 \cdot 10^5$	$> 10^7$	$3,85 \cdot 10^5$
3	$4,27 \cdot 10^5$	$2,06 \cdot 10^6$	----	$4,40 \cdot 10^5$
4	$5,60 \cdot 10^5$	$3,09 \cdot 10^5$	$1,58 \cdot 10^6$	$3,30 \cdot 10^5$
5	$6,80 \cdot 10^5$	$1,99 \cdot 10^6$	$> 10^7$	$3,90 \cdot 10^5$
6	$7,05 \cdot 10^5$	$3,56 \cdot 10^5$	$2,14 \cdot 10^6$	$5,60 \cdot 10^5$
7	$9,30 \cdot 10^5$	$2,57 \cdot 10^5$	$1,00 \cdot 10^6$	$1,50 \cdot 10^6$
8	----	$6,29 \cdot 10^5$	$5,40 \cdot 10^5$	$4,35 \cdot 10^5$
9	----	$3,85 \cdot 10^5$	$8,30 \cdot 10^5$	----

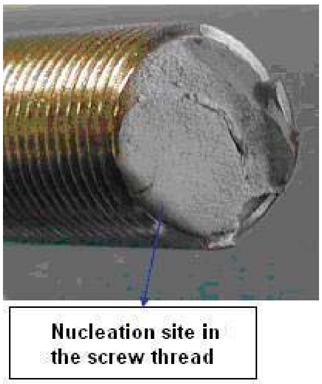
For the samples 2 and 5 of Alloy 2, the test was interrupted for reaching a lifespan superior to 10^7 cycles. The Table 6 presents the life results B10 and B90 for the analyzed bolts.

Table 6. Life B10 and B90 for the analyzed bolts.

	SAE 4140		
θ	**B**	**B10 [cycles]**	**B90 [cycles]**
696652,8	3,517	$3,67 \cdot 10^5$	$8,83 \cdot 10^5$
	Alloy 1		
θ	**B**	**B10 [cycles]**	**B90 [cycles]**
1119623,0	1,590	$2,72 \cdot 10^5$	$1,89 \cdot 10^6$
	Alloy 2		
θ	**B**	**B10 [cycles]**	**B90 [cycles]**
1329197,0	2,254	$4,89 \cdot 10^5$	$1,92 \cdot 10^6$
	Alloy 3		
θ	**B**	**B10 [cycles]**	**B90 [cycles]**
611308,3	2,866	$2,78 \cdot 10^5$	$8,10 \cdot 10^5$



(a)



(b)

Figure 12. (a) Example of a fracture surface of the material of the Alloy 3. (b) Small area of crack propagation is observed.

The macrographic analysis of the surface fracture (Figure 12) showed two fronts of slow propagation of crack, nucleated in the root of the screw thread, which is the most required part of the pin. The growth happened in semi-elliptical form, leaving behind itself beach marks, a fact that establishes an outstanding characteristic in the process of crack propagation for the mechanism of fatigue for alternate bending. The fractographic analyses of the main surface of the fracture showed the nucleation places in the root of the thread. Some resulting defects from the operation of rolling of the thread, which worked as nucleators of the cracks that spread obliquely in the section of the bolt were found. It was observed that Alloy 2 presented the best result in fatigue, probably for the addition of the chrome and a larger percentage (in weight) of carbon in the chemical composition, as can be seen in the Table 1.

4. CONCLUSIONS

This work showed that it is possible to develop bolts for springs starting from national material, in development in the market. After the fatigue tests, it was observed that among the selected materials, Alloy 2, which had the addition of Cr, presented results of fatigue superior to the ones of the quenched and tempered bolt SAE 4140, followed for the of the Alloy 3. Alloy 3, although presented resistance parameters to tension higher than the others for the deformation levels used, had a reduced life to fatigue, probably due to the high quantity of Si in its alloy, forming particles of second phase that should be prematurely nucleating cracks. This fact should still be confirmed.

5. THANKS

The authors express their gratitude to RNA Rassini-NHK Auto Peças S/A. for supplying the material, as well as to the Department of Material, Aeronautics and Automobile Engineering of EESC - USP for the use of its facilities.

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7. RESPONSIBILITY NOTICE

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