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Modified Steels for Cold-Forming U-Bolts Used In Leaf Springs Systems

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In this work, a low alloy steel and a fabrication process were developed to produce U-Bolts for commercial vehicles. Thus, initially five types of no-heat treated steel were developed with different additions of chrome, nickel, and silicon to produce strain hardening effect during cold-forming processing of the U-Bolts, assuring the required mechanical properties. The new materials exhibited a fine perlite and ferrite microstructure due to aluminum and vanadium additions, well known as grain size refiners. The mechanical properties were evaluated in a servo-hydraulic test machine system—MTS 810 according to ASTM A370-03; E739 and E08m-00 standards. The microstructure and fractography analyses of the cold-formed steels were performed by using optical and scanning electronic microscope techniques. To evaluate the performance of the steels and the production process, fatigue tests were carried out under load control (tensile-tensile), $R = 0.1$ and $f = 30$ Hz. The Weibull statistic methodology was used for the analysis of the fatigue results. At the end of this work the 0.21% chrome content steel, Alloy 2, presented the best fatigue performance.

Keywords cold forming, leaf spring, low steel, U-bolts

1. Introduction

Over the last decades, there has been a growing interest from the automotive industry in reducing costs of productive processes and in aggregating new technologies in vehicles' components. New materials and processes showed constant development in an attempt to improve the mechanical properties of these parts. The combination of adding alloying elements to steels and more ambitious production processes have proved to be a quite viable way in obtaining the required results. This tendency has also been observed in the production of suspension systems of automotives vehicles, which are constituted of leaf springs kept together using U-bolts.

The bolt aims to maintain the leaf springs attached to the axis of the vehicle, forming a three components solid set: the axis, the leaf springs, and the supporting plate (see Fig. 1). These parts are combined in the vehicles' suspension system, forming a complex union with the U-bolt, and each of them presents its own effect on the performance of the whole system. They work under action and reaction forces, always in the opposite direction than that of the springs; the bolts themselves support all the tensile stresses generated by the suspension during the working cycles.

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The suspension once is set, will be dynamically loaded and a minimum force of turning moment should previously be applied or the U-bolt will fail by fatigue (Ref 1, 2).

Figure 1 shows the suspension system submitted to a force *F* originated from the maximum stress to which the spring may be submitted during work (Ref 3). Thus, the bolts support the maximum tensile stress. Geometrically, the bolts are square or round as showed in Fig. 2(a) and (b), respectively.

Bolts are usually manufactured employing SAE 4140 steel in the quenched and tempered condition to obtain a tempered martensite microstructure to ensure the level of the necessary mechanical resistance for this type of component. The flow chart diagram in Fig. 3 presents the complex productive process of the SAE 4140 steel bolt, in which the bolts are submitted to a forming temperature of 850 °C and the subsequent heat treatment at 900 °C, and then quenched in oil and tempered at 460 °C for the expected hardness.

Several improvements in the steel mills were implemented, such as reduction of the decarburizing in the raw materials through continuous ingot casting, control of furnaces atmosphere, change in the heating mode (usually oil combustion) to gas, improvement of temperature control, use of adequate quench hardening, continuous tempering furnaces to obtain more homogeneous hardness, implementation of automatic defects control in the rolling mill that allows the detection of them during the process, etc. However, hot work and heat treatment processes create some problems that affect the in service U-bolt performance, as decarburizing, cracks, undesirable phase transformation products, etc.

The cold-forming process is one of the production processes that has received great attention as one of the possible methods in producing automotive components with an improved mechanical and fatigue resistances, without the need of any posteriori heat treatment. Mechanical parts that need to be heat treated are more expensive due to consumption of gas or electricity used for heating, and it also requires

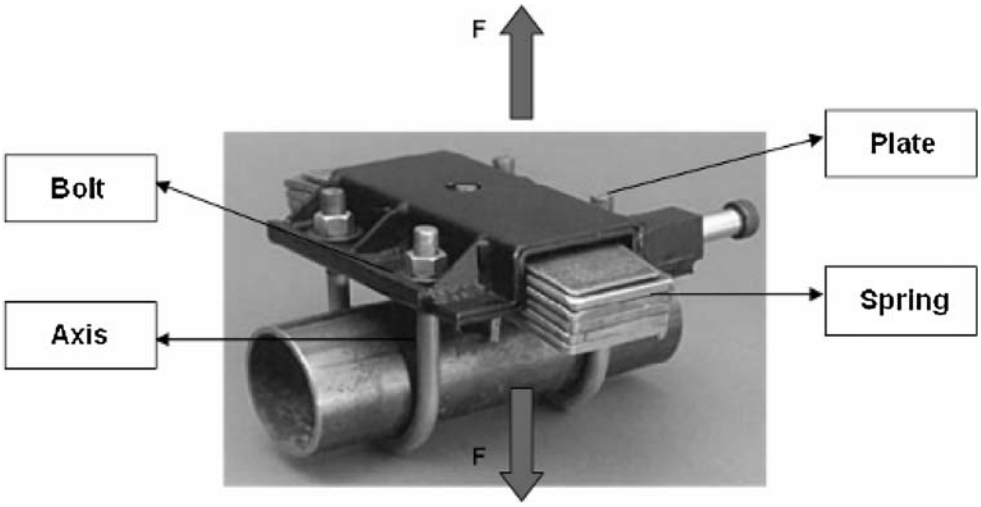

Fig. 1 Outline showing the system of fixation and the direction of the forces to which it is submitted the spring steel

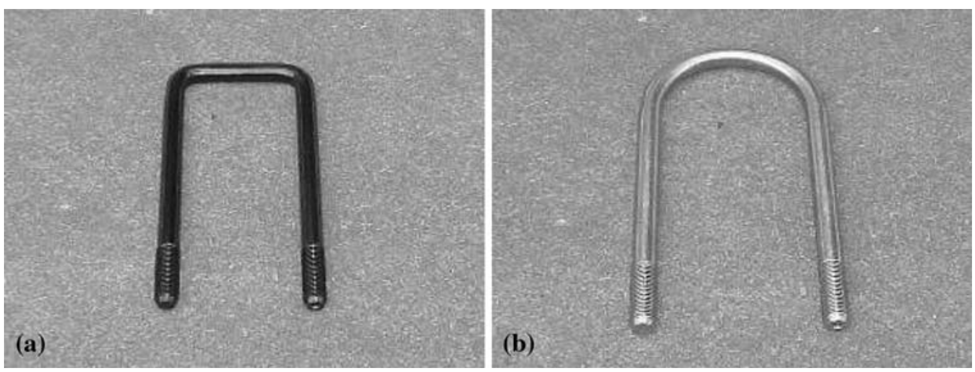

Fig. 2 Shapes of the bolts used in suspensions of vehicles: (a) square and (b) round

a more precise control of temperatures and time of treatment, and if this fails, several problems may occur as mentioned before.

2. Materials and Methods

2.1 Material

The SAE 4140 steel was used as the base line material in this project, since it is the regular material used to produce U-bolt for suspensions systems composed of leaf springs. However, the aim of this work was to produce U-bolts with the necessary mechanical and fatigue properties without the quenching and tempering heat treatments, necessaries in the case of the SAE 4140. Furthermore, it was observed that its chemical composition is not suitable to ensure the necessary mechanical properties and fatigue resistance obtained through strain hardening effect.

From literature and steel producers' knowledge in alloying elements effect, it was possible to select the alloying elements to produce the studied steels with the required mechanical properties without heat treatment process. Once the steels were selected and produced, a previous analysis was carried out using tensile tests to establish the amount of plastic deformation during the drawing process (Ref 4).

Therefore, bars from the proposed steels were obtained by drawing process to promote a general increase of the mechanical resistance by strain hardening effect. To increase this strength even further, to this previous deformation an additional local deformation was carried out during the cold forming of the thread regions by a special rolling process. The bolts were manufactured in a U format with the preselected threads (M12 × 1.25) on it (Ref 5). Figure 4 presents the geometry and dimensions of the U-bolts. The material chemical analysis of the selected steels was carried out using an optical spectrometry by arc Mod 3460.

For microstructural evaluation, samples were removed from the thread (root and crest) and A and B regions, on the longitudinal and transversal directions as indicated in Fig. 4. In all cases, the analyses were carried out on the surface and in the center of the bar. The removed samples were grounded, polished, and etched with 2% Nital. Finally, they were observed in an optical microscope in conjunction with a Buehler Omnimet Enterprise image analyzer for grain size (GS) evaluation on the transversal direction. From the microstructural evaluation, it was possible to verify the microstructure composition and the average GS following the ASTM E112-96 standard (Ref 6), as well as the decarburizing and discontinuities present in the steels.

2.2 Hardness and Tensile Tests

Measures of hardness were performed in samples removed from the bars after drawing and in the thread region in a

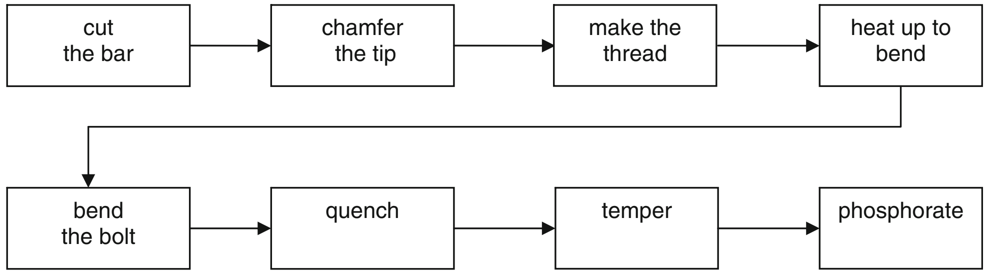

Fig. 3 Flow chart of bolt production in the hot-forming process

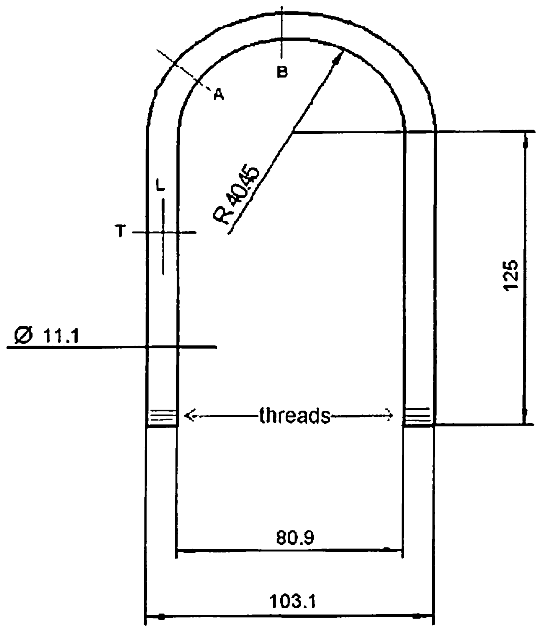

Fig. 4 Geometry and dimensions of the U-bolts. Dimensions in mm

Universal Hardness Equipment, Rockwell C scale, and using the load of 150 kgf. Four measurements were performed on the surface as shown in Fig. 5(a). For the evaluation of cold work effect on the thread root due to the rolling process, 10 Vickers hardness measurements were carried out starting just below the thread root until the center of the bar (Fig. 5b).

To evaluate the general tensile strength of the bar after the drawing process, samples were prepared and carried out according to ASTM E8M-00 standard (Ref 7, 8), at speed testing of 1.0 mm/min in a EMIC DL10000 mechanical machine. The specimens' geometry and dimensions are presented in Fig. 6. Three samples were tested for each studied steel.

2.3 Fatigue Tests

As the U-bolt is submitted to repeated load, fatigue failure is a major concern and a factor to be considered in the procedure for selection of its steel and fabrication process. Therefore, fatigue tests were performed at the same stress level, since the aim of this work was the selection of a steel for U-bolt production using cold-forming processes. The fatigue tests were performed according to ASTM E466-96 (Ref 9) in laboratory air and at room temperature. The tests were computer controlled, using a servo-hydraulic MTS 810 universal testing machine under load control, sinusoidal wave form, 30 Hz frequency and stress ratio, $R = 0.1$.

Initially, an attempt was made in testing the component as it is. For that, it was necessary to produce grips as shown in Fig. 7(a). However, this system did not allowed the bolt to be perfectly aligned and premature fracture occurred in one side only, which made this method inappropriate for testing. However, it has been noticed from the literature (Ref 3, 5) that, in the case of U-bolts, the most critical section is the thread regions. Therefore, specimens contained the threaded region were obtained directly from the U-bolts, as shown in Fig. 7(c). Thus, a special test support and a regular hydraulic grip were used as shown in Fig. 7(b). The smooth part of the sample was attached to the hydraulic grip, while the threaded part was fixed to the special support using the U-bolt nut. Figure 7(d) shows a specimen read to be tested.

Weibull statistics analysis was used for fatigue data evaluation. The criterion used to evaluate the fatigue performance was the life B10 and B90, where B10 represents that 10% of the specimens can fracture below the specified minimum life and B90 represents that 90% of the specimens can have a superior life to the specified. In this analysis, a minimum of eight specimens of each material were submitted to fatigue under the same stress range previously determined based on the mechanical properties of the material. This method provides 90% percentage of replication, i.e., by the calculation of total number of samples used as presented by the ASTM E739-91 standard (Ref 10). The fatigue results are presented as curves of probability to failure, $F(N_f)$, versus N_f, where N_f is the number of cycles necessary for total failure of the specimens. In these analyses, the two Weibull parameters (m, θ) are used for the model.

The two parameter Weibull distribution function is given in Eq 1.

$$F(N_f) = 1 - e^{-\left(\frac{N_f}{\theta}\right)^m} \quad \text{(Eq 1)}$$

where $F(N_f)$ is failure probability or failure frequency, N_f is the fatigue life, θ is the characteristic life, the point at which 63.2% of the units were faulty and m is the shape parameter, i.e., the slope of the Weibull chart.

3. Results and Discussions

Table 1 presents the chemical analysis results for the selected low alloy steels used in this study. As can be seen

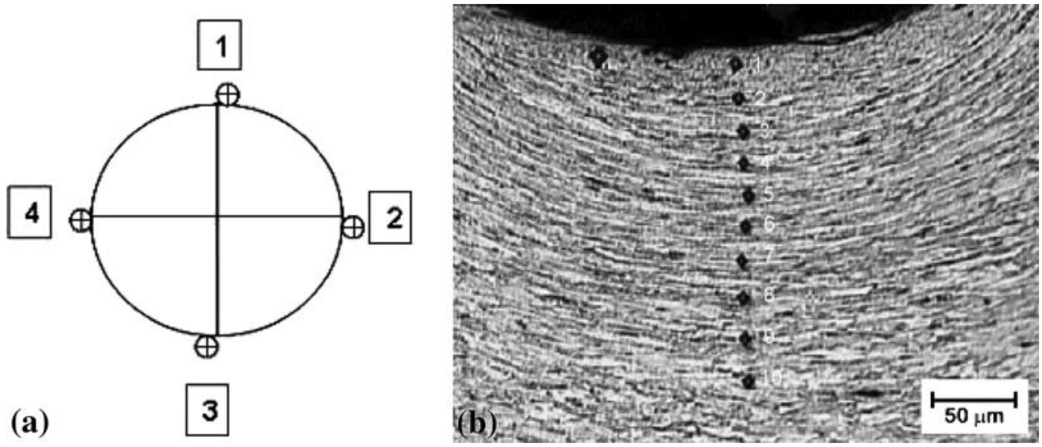

Fig. 5 Positions of hardness measurement. (a) On the steel bar and (b) microhardness profile, starting from the screw thread root in Alloy 1. It is also observed the deformation lines from the rolling process. Values are presented in Table 3

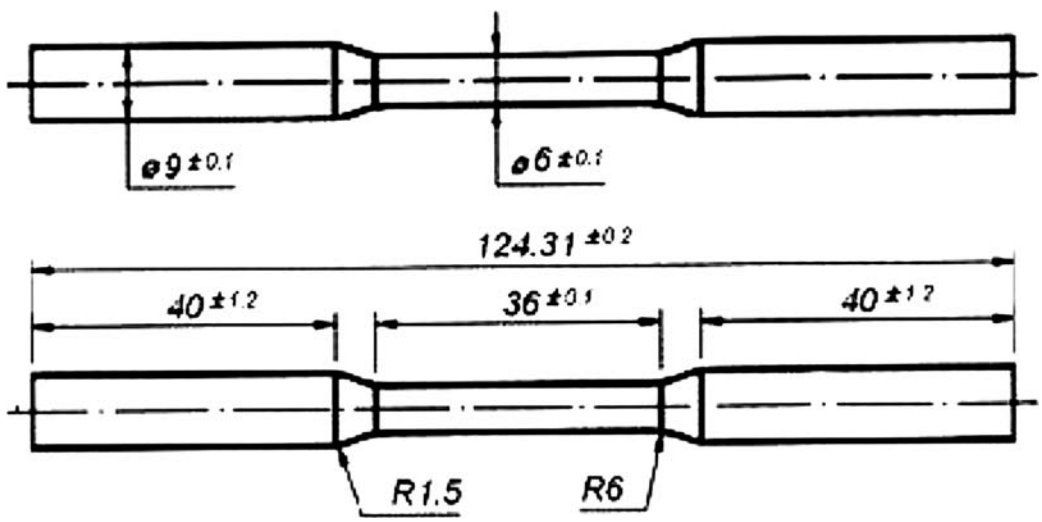

Fig. 6 Geometry and dimensions of the tension test specimens (Ref 1)

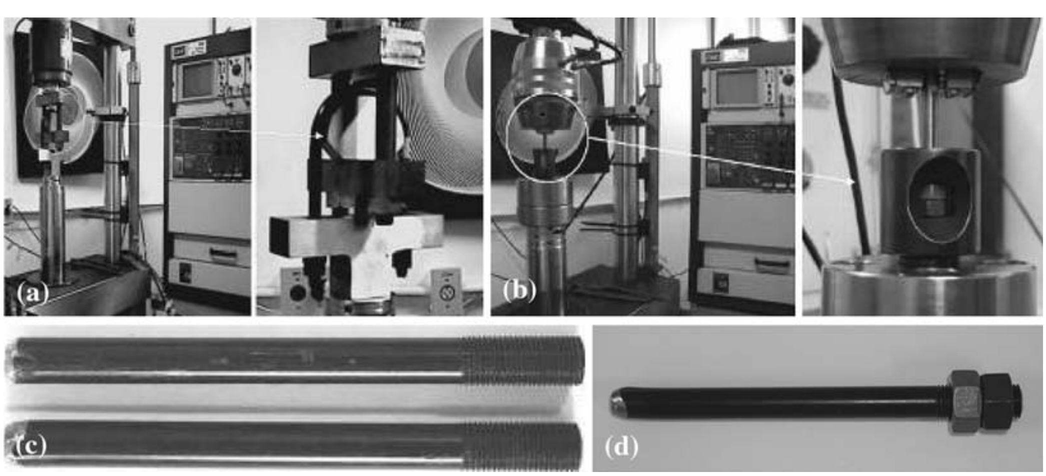

Fig. 7 Fatigue test: (a) and (b) assembling; (c) sample removed from the bolts; and (d) sample ready to be tested

the alloying, some alloying elements were added based on the following:

(a) *Silicon*: It was used in the range of 0.2-0.64 wt.%. It constitutes an impurity in steels does not have a great influence in their properties. To verify this influence, an alloy with minimum level and other with the maximum level of this element was prepared.
(b) *Chrome*: It was added in Alloys 1, 2, and 3 to increase the hardness and the yield strength; however, Alloy 3 presented the lowest amount of this alloying element (0.13 wt.%), due to the fact that a very high amount of Ni and Si were added, already.
(c) *Nickel*: In Alloy 1 the nickel addition was discreet because the percentages of carbon and chrome were higher than in Alloys 2 and 3. In these two (Alloys 2 and 3), nickel was added to increase the tensile strength, yield point, hardness, and toughness.
(d) *Aluminum and vanadium*: They were combined to provide an effective average GS refinement (Ref 6), which contributes to improve the mechanical strength and the fatigue resistance, as well as the cold-forming behavior in the bending operation.

Table 2 presents the start and final gauges, as well as the true strain, obtained from the drawing process that has produced the first strain hardening effect on the selected alloys. It can be observed that in all cases a similar level of plastic deformation was used to cause the necessary strain hardening effect.

From Table 3, it is possible to observe that, as expected, a progressive decrease in the hardness values with the increase of the distance from the threads' root, showing that the rolling process to produce the threads, succeeded in increase the local mechanical properties, certainly giving to this region an increased fatigue resistance.

For the calculation of the maximum applied stress to the specimens during tests, it is necessary to consider the fatigue stress concentration factor, K_f at the threaded section (Ref 11, 12). This factor is usually obtained in the literature (Ref 2) and it depends on the geometrical characteristics of the thread, root's radius and depth, as well as on the materials properties (γ).

For the employed thread type, i.e., M12 × 1.25, where the screw pitch, b, is 1.25 mm, nominal root radio, r, is 0.180 mm, and the screw high, t, is 0.767 mm, according to ASME B1.13 M-01 and the Neuber analysis (Ref 5, 12), for $b/t = 1.63$, leads to coefficient of load relief due to the decrease in the stress concentration factor caused by a series of identical closely spaced notches or grooves, γ of 0.5, as shown in Fig. 8. Therefore:

$$K_t = 1 + 2\left(\frac{\gamma * t}{r}\right)^{0.5} \quad \text{(Eq 2)}$$

$$K_t = 1 + 2\left(\frac{0.5 * 0.767}{0.180}\right)^{0.5} = 3.92$$

For K_f calculation, the average value of the characteristic length, a, obtained by the Peterson, R.E. diagram (Ref 5), is found to be 0.095 mm. For r value used (0.180 mm), K_t calculated above and following the ASME B1.13M-01 standard (Ref 5), yields:

$$K_f = 1 + \frac{K_t - 1}{\left(1 + \frac{a}{r}\right)} \quad \text{(Eq 3)}$$

$$K_f = 1 + \frac{3.92 - 1}{\left(1 + \frac{0.095}{0.180}\right)} = 2.91$$

Thus, the values of K_f are approximately 26% smaller than the values of K_t in the root of the thread.

Table 1 Chemical compositions for SAE 4140 steel and the proposed alloys (wt.%)

Alloys	SAE 4140	Alloy 1	Alloy 2	Alloy 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 (max)	0.017	0.016	0.014
S	0.05 (max)	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	···	···

P.S. max = maximum

Table 2 Amount of total true strain applied to increase the mechanical strength for the mentioned alloys

Alloys	Starting gauge, mm	Final gauge, mm	ε_{VT}, %*
1	12.70	11.09	27.11
2	12.70	11.06	27.65
3	12.70	11.06	27.65

*ε_{VT} (%) = ln(A_o/A_f)*100, where A_f and A_o are the final and initial areas, respectively

Table 3 Values of hardness measured on the bar's surface and in the threads' root, as shown in Fig. 5

Measurement	SAE 4140	Alloy 1	Alloy 2	Alloy 3
Bar's surface, HRC				
Mean (4 points)	27.5	28.5	22.3	32.8
Threads' root, 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

Figures 9-12 show the microstructure for the SAE 4140 steel (quenched and tempered) and for the Alloys 1, 2, and 3, respectively.

As mentioned before, currently, the U-bolts manufacture process includes heat treatment, i.e., quench and temper. Thus, the SAE 4140 presented a microstructure of tempered martensite and it was also observed some segregation lines (Fig. 9b). Figure 9(c) presents a general aspect of the microstructure in the screw region where on the crest it was observed the presence of micro-cracks (Fig. 9d). In Fig. 9(c), it is observed the presence of a superficial layer (duo-chrome-plated layer) used in this route of U-bolt producing process. This aspect may induce to the misinterpretation of a decarburized case; however, from Fig. 9(d) it is clear that decarburizing was not present. The highest amount of Al and V presented in Alloy 3 contributed to the very fine average GS number 9-11 (Ref 6) found for this case, see Table 4.

Alloys 1, 2, and 3 presented a very similar microstructure, i.e., they are constituted of perlite and ferrite (white), as shown

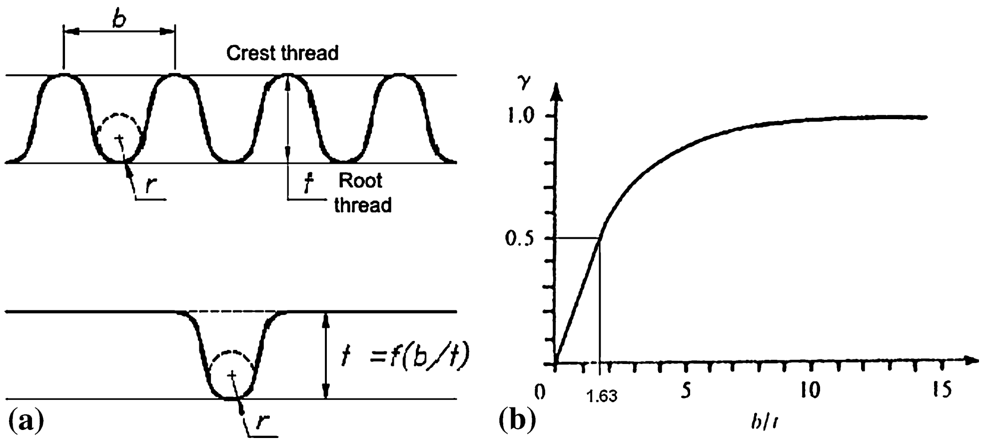

Fig. 8 (a) Thread's geometric parameters. (b) Geometric factor γ versus *b*/*t*

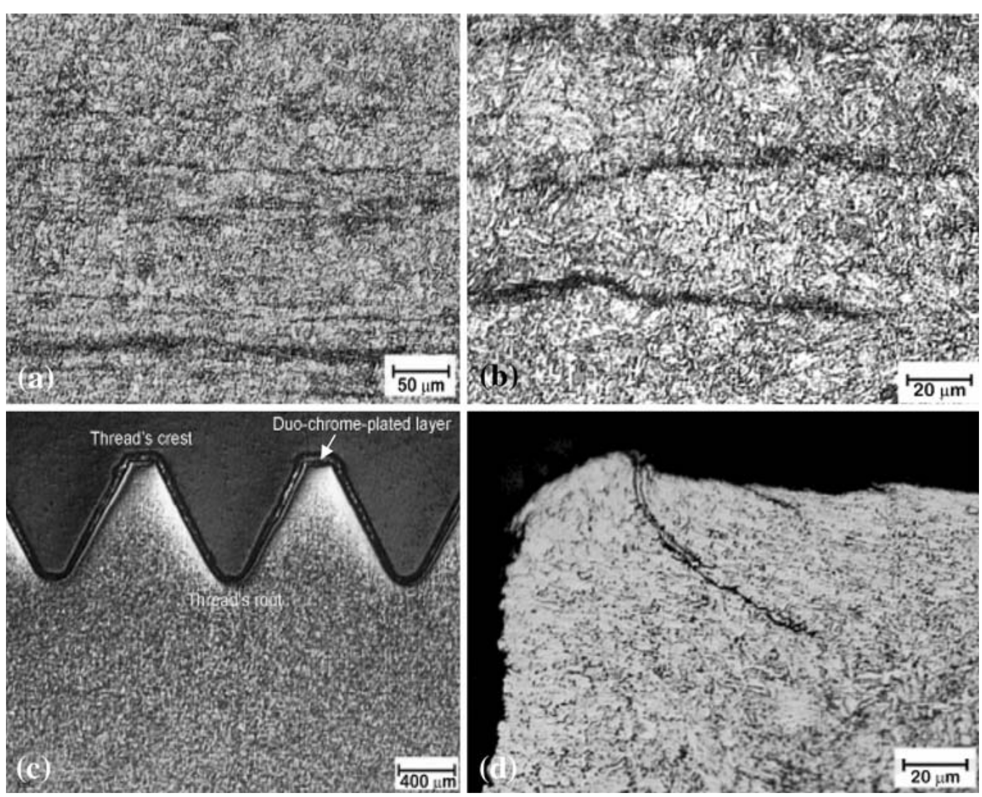

Fig. 9 Microstructure of SAE 4140 steel after quenching and tempering, traverse direction: (a) tempered martensite and (b) detail of (a) showing segregation lines, (c) general aspect of the profile of the thread; (d) detail of (c) showing microcracks that appeared during quenching

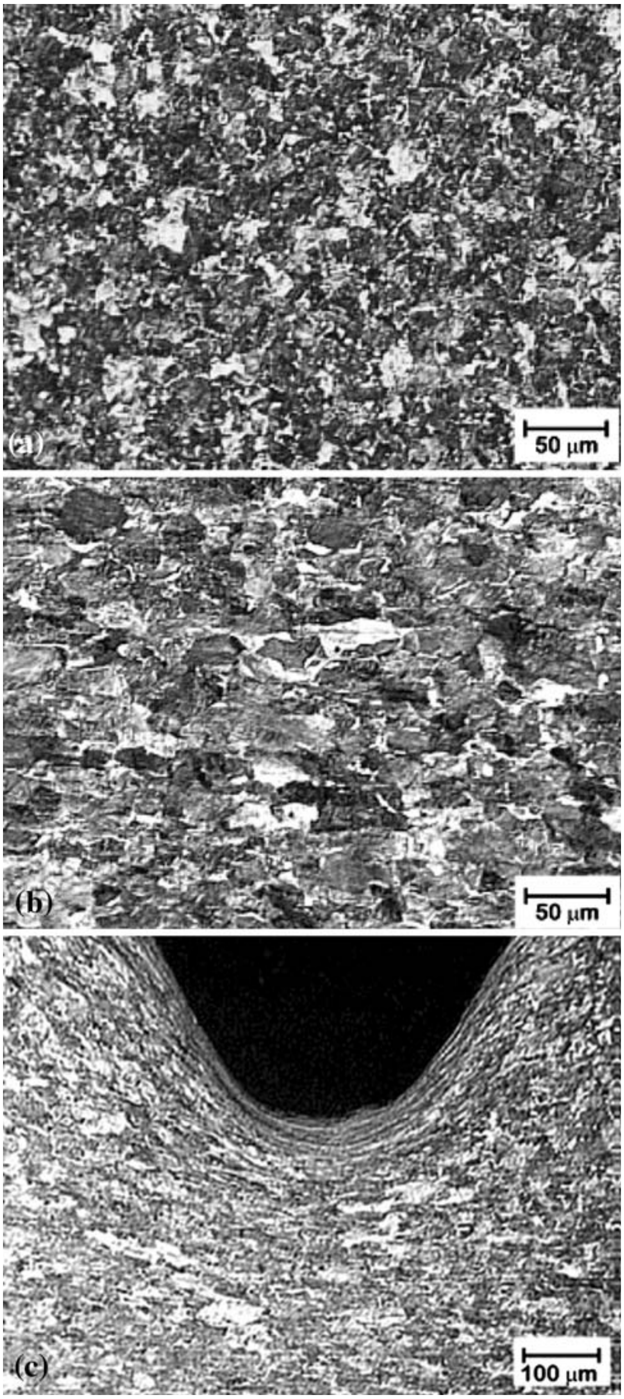

Fig. 10 Microstructures of the Alloy 1: (a) transverse direction and (b) longitudinal direction. (c) Profile of the thread

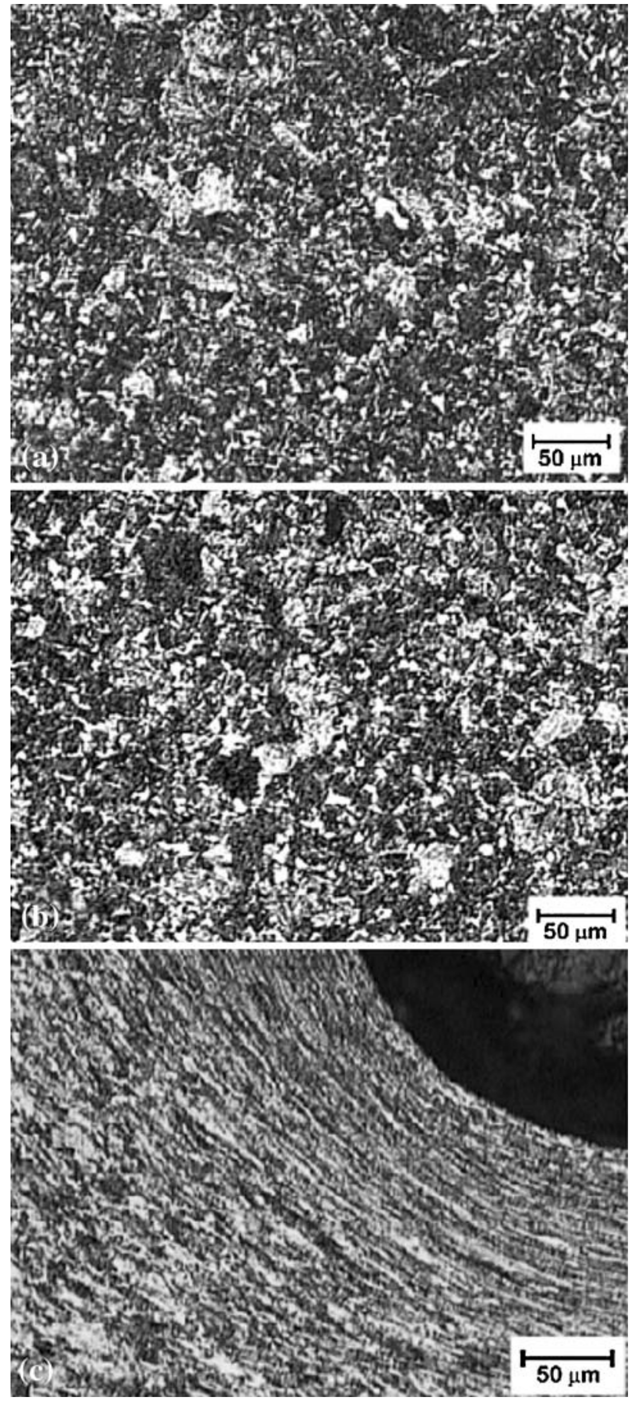

Fig. 11 Microstructures of the Alloy 2: (a) transverse direction and (b) longitudinal direction. (c) Profile of the thread

in Fig. 10 and 11. The only accounted difference is in the amount of each phase (ferrite and perlite) and GS. In Fig. 11, it is seen that the thread process has caused a great amount of superficial plastic deformation on the root, as well as in the thread's crest (Fig. 12c).

Table 3 presents the results from hardness measurements carried out on the bar's surface and the hardness profile starting from the thread root toward to the center. It was observed that Alloy 3 presented the highest hardness value (32.8 HRC), followed by Alloy 1 (28.0 HRC) and Alloy 2 (22.4 HRC). Comparing these results with the ones obtained from the tensile test and microstructure evaluation, Table 4, it can be seen that the cold-forming process was effective in producing a very strong strain hardening effect (Alloys 1-3), in conjunction with a finer GS (fine perlite microstructure), tensile strength similar to the quenched and tempered steel. At the thread root, the surface hardness value for Alloy 3 is much higher than the value obtained for the quenched and tempered steel, this

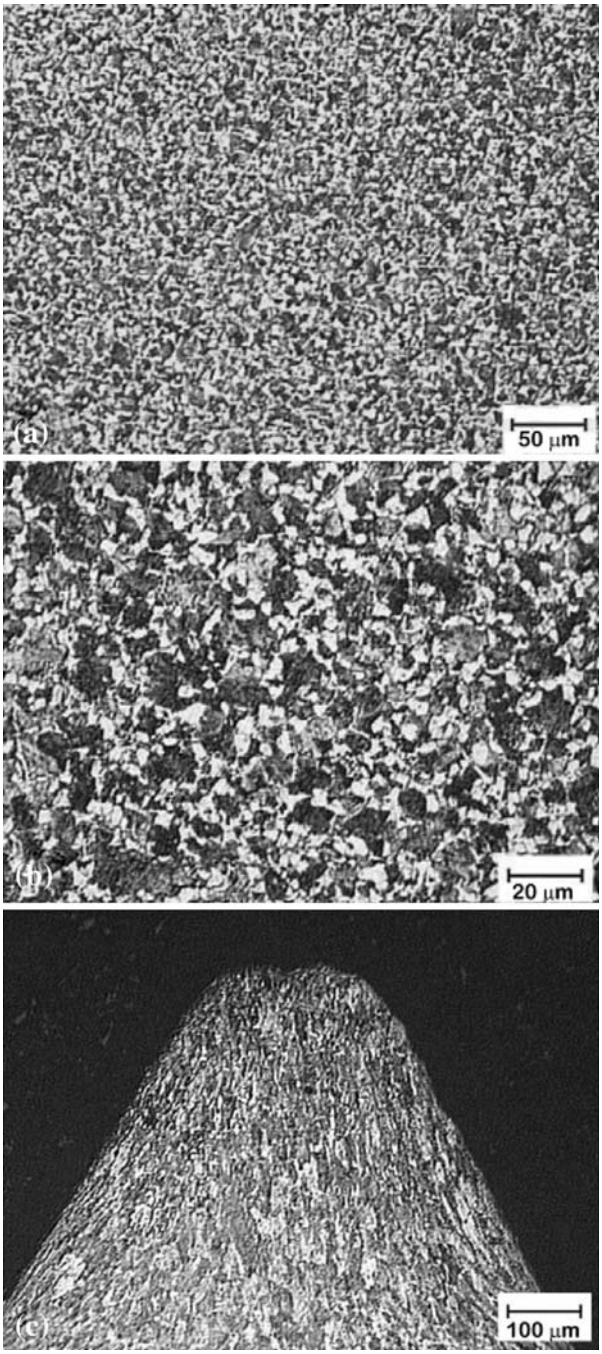

Fig. 12 Microstructures of the Alloy 3: (a) transverse direction and (b) longitudinal direction. (c) Profile of the thread's crest

certainly will have a beneficial effect on the fatigue life of the component, as will be seen later. This grain refinement and strain hardening ability are directly associated to the alloying addition, as mentioned before.

Alloy 3 showed better values mechanical strength, especially higher tensile strength, and once the U-bolt works under cyclic tension-tension loading should be expected that it would exhibit a better in service performance. However, due to Alloy 3 exhibited the highest bar's hardness, it may be considered that during the thread rolling process, this property may affect this process and generate some stress concentration in the thread profile.

Table 5 presents the results of the fatigue life for the studied steels. The probability of failure versus fatigue life curves was obtained using a computer program denominated Weibull 7.0 that calculates the Weibull's statistical distribution.

The specimens 2 and 5 from Alloy 2, the tests were interrupted because both lives were superior to 10^7 cycles (run-out). Table 6 presents the life results for B10 and B90 probabilities.

Table 5 Fatigue life results of the bolts

	Materials/fatigue life (cycles)			
Samples	**SAE 4140**	**Alloy 1**	**Alloy 2**	**Alloy 3**
1	···	1.10×10^6	9.60×10^5	5.83×10^5
2	3.80×10^5	6.06×10^5	$>10^7$*	3.85×10^5
3	4.27×10^5	2.06×10^6	···	4.40×10^5
4	5.60×10^5	3.09×10^5	1.58×10^6	3.30×10^5
5	6.80×10^5	1.99×10^6	$>10^7$*	3.90×10^5
6	7.05×10^5	3.56×10^5	2.14×10^6	5.60×10^5
7	9.30×10^5	2.57×10^5	1.00×10^6	1.50×10^6
8	···	6.29×10^5	5.40×10^5	4.35×10^5
9	···	3.85×10^5	8.30×10^5	···

Obs: *Specimens 2 and 5 from Alloy 2 the testing was interrupted by reaching the projected run-out (10^7 cycles)
Dotted line (···) means that the samples were lost due to overloading or other testing problem

Table 6 Fatigue B10 and B90 lives for the bolts

	θ	***m***	**B10, cycles**	**B90, cycles**
SAE 4140	696652.8	3.517	3.67×10^5	8.83×10^5
Alloy 1	1119623.0	1.590	2.72×10^5	1.89×10^6
Alloy 2	1329197.0	2.254	4.89×10^5	1.92×10^6
Alloy 3	611308.3	2.866	2.78×10^5	8.10×10^5

Table 4 Tensile properties and microstructure of the alloys used in this work

Properties	**σ_R, MPa**	**σ_y, MPa**	**El, %**	**Microstructure**	**GS, ASTM**
Designed	900, min	720, min	10, min	Fine perlite	8/more fine
SAE 4140	1052.7 ± 0.9	950.5 ± 1.2	12.1 ± 0.3	Temp. marten.	6-7
Alloy 1	1054.6 ± 1.2	950.5 ± 1.2	11.6 ± 0.2	Fine perlite	7-8
Alloy 2	1053.1 ± 0.5	839.1 ± 1.1	13.2 ± 0.4	Fine perlite	8-10
Alloy 3	1053.4 ± 0.9	886.5 ± 1.0	9.3 ± 0.3	Fine perlite	9-11

σ_R (MPa), tensile strength; σ_y (MPa), yield point; El (%), elongation (25 mm gauge length); GS (ASTM), average grain size by ASTM E112-00; min, minimum

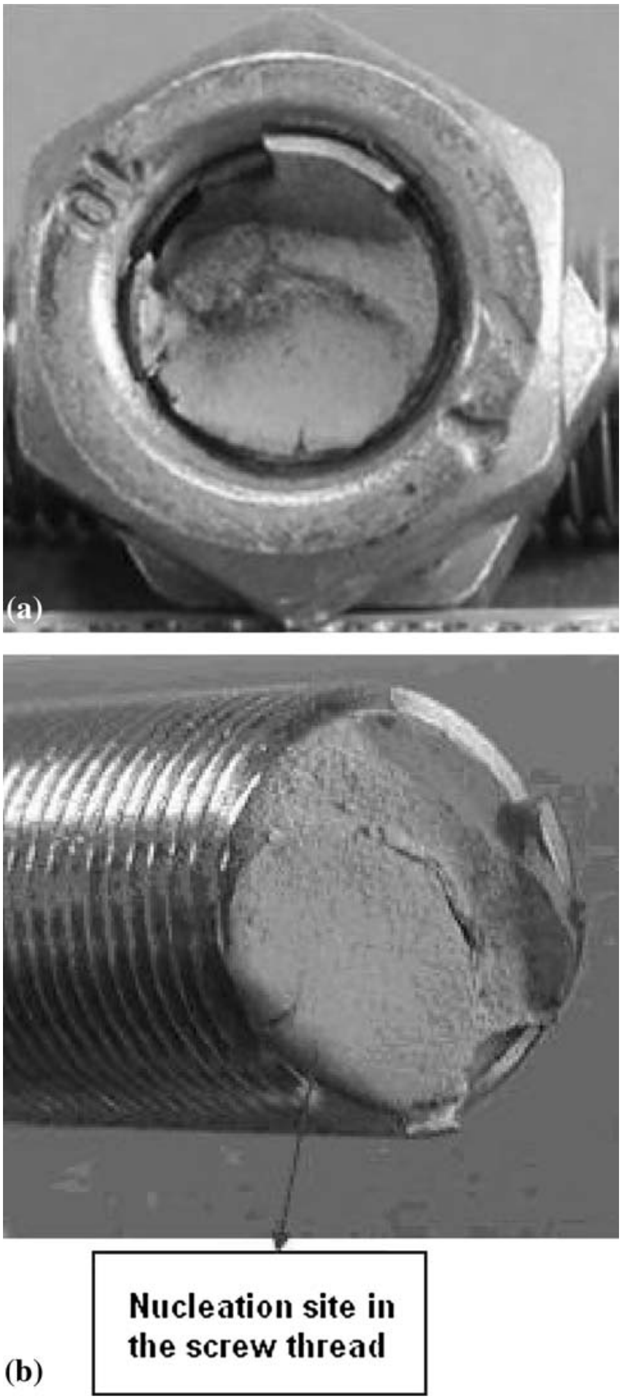

Fig. 13 (a) Example of a fracture surface of Alloy 3. (b) Small area of crack propagation is observed

The fractographic analysis of the surface fracture, Fig. 13, showed two fronts of slow crack propagation, nucleated at the root of the thread, which presents the highest local stress, and the growth took place in semi-elliptical form.

From Table 5, it is concluded that Alloy 2 presented the best results in fatigue, probably due to its chemical composition that provided the best association between ductility and mechanical strength, since the threads are produced by a forming process.

4. Conclusions

This work showed that it is possible to develop low alloy steels and a cold work process (without the use of heat treatments) for U-bolts used in the leaf suspension springs.

In this way, Alloy 2 presented the best fatigue performance, due to Cr addition. The fatigue results showed to be superior to the quenched and tempered bolt produced using SAE 4140, followed by Alloy 3.

Alloy 3, although presenting tensile parameters resistance higher than the others for the deformation levels employed, had the fatigue life reduced (Ref 2), probably due to the high quantity of Si addicted to the prior steel, which allowed the formation of second phase particles and nucleating cracks prematurely.

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