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Research paper

Surface processing to improve the fatigue strength of bainitic steels – An overview

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Abstract

Currently, one of the major challenges for automotive industries is to reduce the weight and energy consumption of vehicles by using stronger and advanced low-cost materials. Conventional solutions using quenched and tempered steels not always fulfill the desired technical, economic and environmental requirements. Modern continuous cooling bainitic steels can provide a good combination of mechanical strength and toughness, being considered an excellent alternative to replace quenched and tempered martensitic steels in the manufacture of forged components. To meet the desired industry standards in highly loaded components, properties like surface hardness, fatigue strength, wear and friction resistance of these steels can be further improved by subsequent mechanical and thermochemical treatments. Therefore, this paper presents the state of the art in the use of continuous cooling bainitic steels for forging and low energy consumption surface improvement techniques such as: deep rolling and plasma nitriding. Finally, case studies are presented, and conclusions drawn on the current trends and reported practices. Surface modification techniques must be carefully controlled and combined with the material of interest to ensure that undesirable characteristics are not introduced during the manufacturing of the components. The development of processes based on the use of forged continuous cooling bainitic steels can be an excellent alternative to replace the conventional quenching and tempering treatment with considerable reduction of the energy consumption.

Keywords: *Bainitic Steels; Deep Rolling; Plasma Nitriding; Energy Saving; Automotive Applications.*

1. Introduction

The industrial sector is responsible for over 50% of the energy demand worldwide [1]. Given this scenario, the savings obtained in energy efficient actions in the industrial sector represent benefits for whole society and the environment. In the metal forming industry, actions such as heating and reheating of material as well as heat treatment furnaces are among the major responsible for high consumption [2]. In hot and warm forging, the parts need to be heated to the forging temperatures in order to reduce the yield stress and increase the deformability. After forging this heat is generally lost to the environment. In the conventional processing route, the forgings need to be reheated for the indispensable tempering of the martensitic microstructure. Processes such as direct quenching emerged to take advantage of this heat and reduce energy waste [2], [3].

The use of new bainitic steels for forging can be an alternative to make the processes of manufacture of hot forged parts more flexible. Traditional process of quenching and tempering could be replaced by controlled or continuous cooling, contributing to the reduction of energy consumption in the manufacturing processes. The controlled cooling of the bainitic steels immediately after the hot forging can produce an adequate cooling rate for the development of the bainitic microstructure and consequently provide a good compromise between hardness, toughness and fatigue strength [3–5].

In order to obtain a steel with a microstructure that presents adequate properties (similar or better than quenched and tempered steels), several research groups [6–10] have focused their studies on the development of refined bainitic microstructure. In some studies [9], [11] the development of a nanostructured bainitic microstructure, also called Super-Bainite, has been reported. In the Nanobain project, with support from the European Union, a bainitic microstructure free of carbides and containing retained austenite has been developed. The metallic materials processing seeking for energy saving and near net shape is being called Green Manufacturing. This paradigm topic has been explored in several research projects, as in the case of the AiF–DFG joint program EcoForge [12]. The developed innovative process chain was designed to obtain a ductile bainite microstructure by continuous cooling directly after the forging. Fig. 1 summarizes recent developments in forging steels according Charpy impact energy vs. Yield strength diagram [4], [13].

Because these materials have a good combination of mechanical strength and toughness, they are considered an excellent alternative for quenched and tempered martensitic steels [3], [5], [14–18]. The possibility of associating thermochemical treatments with good structural quality of bainitic steels has aroused interest of several researchers [16], [19], [20]. According to Lembke et al. [16], the surface hardness of bainitic steels after nitriding can be compared with that of quenched and tempered steels, making them attractive for many automotive components that are subject to high dynamic loads, friction wear and corrosion [21–23].

Traditionally, the carburizing process is widely used to increase surface hardness and wear strength of mechanical components [24–27], however, due to the process characteristics (high temperature, fast cooling, phase change, etc.), this thermochemical treatment causes, in general, strong deformations and embrittlement of these materials [16], [26], [28].

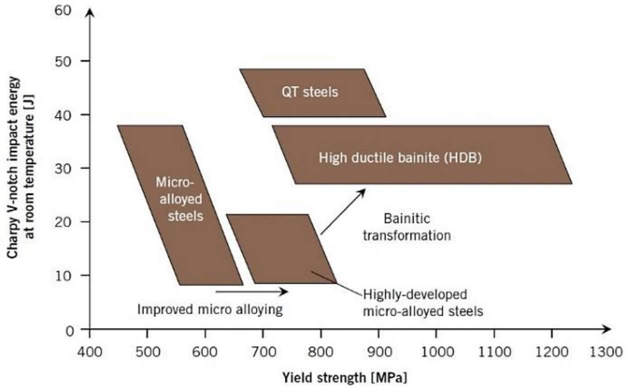

Fig. 1: Main Steel Types Used in the Manufacturing of Parts for the Automotive Industry. Reproduced from [4], [13].

Surface treatments such as plasma nitriding can be carried in lower treatment temperatures [20], [29–32], therefore being more suitable for these steels because it preserves the bainitic microstructure and does not take effect on the core hardness. In addition, this process maintains the congruence with the main philosophy of the energy consumption reduction trend, since this process does not require subsequent stages of quenching and tempering to produce the hardening of the nitrided layer [32–34]. Since the two surface treatment processes have similar objectives, there is potential for plasma nitriding to be used to replace carburizing. However, to make this substitution, several aspects need to be considered, such as: generated deformations, surface hardness, depth of hardened layer and manufacturing costs [24], [26], [32], [35].

Another alternative recently developed to improve the surface properties of the new continuous cooling bainitic steels, without harming the microstructure of these materials, is the deep rolling process [36–40]. In this context, this paper aims to provide an overview of the new continuous cooling bainitic steels for automotive applications and some surface treatment techniques to improve their mechanical properties, keeping low energy consumption.

2. New bainitic steels for automotive industry

Newly developed steels for automotive production must have adequate mechanical properties for them to be used properly in vehicle structure and components [41–44]. As the mechanical properties are primarily a function of the steel's microstructure, which is heavily dependent on the processing conditions such as temperature, strain, strain rate, deformation mode and cooling method used [45], [46], important considerations about these effects will be presented in continuous cooling bainitic steels.

2.1. Effect of thermo mechanical processing on the material properties

Techniques of steel manufacturing involving addition of microalloying elements and strict controls of heating, rolling and cooling can produce microstructures with high mechanical properties, which within certain limits of strength and thickness can be achieved without the need of additional heat treatment after rolling. In general, this procedure is called thermomechanical processing (TMP), through it several categories of steels are obtained [47], [48]. TMP is a metallurgical process that integrates work hardening and heat treatment into a single process to control the final microstructure of the materials and consequently improve their mechanical properties during the hot forming process [49], [50].

The development of TMP steels has been used to promote microstructural refinement, strengthening and hardening of manufactured steel parts [45], [47], [48], [51]. The microstructural refinement is promoted by the combination of controlled rolling with accelerated cooling (ACC) [52]. (Fig. 2) provides an overview of the microstructure evolution in the manufacture of TMP steels with different cooling conditions.

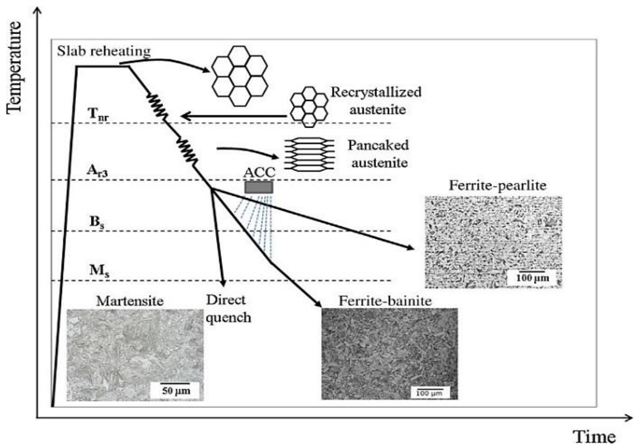

Fig. 2: Schematic of Microstructure Evolution in TMP Steels (T_{nr}: Nonrecrystallization Temperature; Ar_3: Transformation Start Temperature; B_s: Bainite Start Temperature; M_s: Martensite Start Temperature. Reproduced From [52].

The combined effect of the addition of alloying elements to thermomechanical processing allows the exploration of different hardening mechanisms, such as precipitation hardening, grain refinement and phase transformation [45], [53], [54]. The new generation of bainitic steels formed during continuous cooling allows the formation of different bainitic morphologies (granular bainite, upper bainite, lower bainite, etc.) and may contain other phases such as retained austenite and ferrite. Unlike quenched and tempered steels, which obtain their excellent properties after processing steps and subsequent heat treatment, continuous cooling bainitic-martensitic steels already have high levels of strength and toughness after hot rolling or forging without the need for further heat treatment, presenting the potential to shorten its manufacturing cycle, reducing energy consumption and production costs [17], [55], [56].

When it is needed to follow other processing steps (such as machining operations), high strength values and toughness can be detrimental to productivity and cause additional costs during manufacturing. To achieve maximum benefit out of these novel steels they must be designed in such a way that working proprieties and material characteristics are properly balanced. Over the last decade, new low carbon (C-Mn-B) and medium carbon (C-Si-Mn-Cr type) bainitic-martensitic steels have been developed, taking into account possible strategies of air cooling in a conventional hot rolling mill for long products. Steel compositions with high manganese and boron additions in combination with titanium can control the transformation of the austenite-bainite phase and ensures the desired steel microstructure which in the reported case is a cementite-free granular bainite [16], [55].

Refined microstructures with high strength can be obtained by lowering the phase transformation temperature, contributing to the formation of bainitic structures [4], [18]. These steels are designed and manufactured according to conventional thermomechanical processes, and achieve significant combinations of strength and toughness, comparable to quenched and tempered conventional martensitic steels [57], [58]. However, the specific requirements of the automotive industry need to be carefully considered to optimize the chemical composition and processing route [5], [59].

2.2. Influence of alloying elements on microstructure and mechanical properties

The alloying elements can hinder the microstructural evolution control in the processing of high strength steels, due to the final microstructure of these steels that is usually a composite with different combinations of ferrite, martensite, bainite, austenite and precipitates. As a result, it may not be suitable to simply apply the existing thermomechanical processing routes, as with the continued growth of the production of these materials, the strength and quality requirements for the products are becoming increasingly rigid [60]. Therefore, all steel manufacturing steps need to be carefully controlled, and different processing strategies must be adopted to fulfill the specified quality [50].

Bainite microstructure steels presents excellent deformation possibilities for forged components. The variety of different bainitic morphologies requires a heat treatment aligned after forging to achieve maximum performance [61]. Due to the alloy and heat treatment concept, bainite is composed of different microstructural components, such as the primary ferritic phase and the secondary phase, which consists of carbides (martensite and/or austenite). Different combinations of mechanical properties can be adjusted in these steels, depending on the arrangement of the primary and secondary phases [13], [62], [63].

In the Nanobain project, a carbide-free bainitic microstructure, containing retained austenite was developed [64]. Carbide-free bainitic microstructures have considerable potential for automotive application, since they have yield strength over than 1600 MPa, presenting good ductility [8], [57], [61], [65], [66]. Thus, (Fig. 3) shows the comparison between the yield strength and total elongation of the usual commercial steels with the new bainitic steels, which have carbon levels between 0.2 wt.% and 0.3 wt.%.

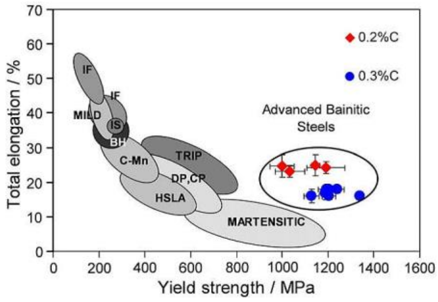

Fig. 3: Yield Strength and Total Elongation of Advanced Bainitic Steels In Comparison with Other Commercial Steel Grades. Reproduced from [57].

General design principles of bainitic steels are found in [7–10], [67–71]. It is well established that the mechanical strength of bainite is controlled mainly by microstructural refinement. This means that the final bainitic transformation temperature should be sufficiently low, which can be achieved with increasing amounts of C, Si, Mn, Cr and Mo. Whereas for steels with content below 0.2 wt.% carbon, the granular bainite is predominantly formed [72]. A great effort was done to characterize the specific properties of different types of bainite and a description of the different morphologies are found in [14], [57], [61], [73]. Although bainitic forging steels exhibit high strength limit values and excellent fatigue strength, these materials must meet special requirements imposed by the manufacturing conditions, such as good formability, weldability and machinability [74], [75].

There have been studies on microstructure and properties relationships [8], [76], [77], crystallography [78], [79], wear behavior [80], [81], and thermal tempering of bainitic steels but it has little to no reported cases aiming to enhance its surface properties [16], [19], [20], [82]. Therefore, there will be presented some surface improvement techniques (with low energy consumption) currently used to improve the mechanical strength of bainitic steels.

3. Surface processing to improve the fatigue strength of steels

Through the development of new steels and processing techniques, there have been corresponding advances in the fatigue performance of automotive parts. These advances have promoted life increase of components subjected to high dynamic loads, friction wear and corrosion [21–23], [39], [40]. In this sense, new processing approaches to improve fatigue performance are reviewed with emphasis on low energy consumption surface treatments such as deep rolling and plasma nitriding. Selected examples are presented to illustrate the importance of the properties of the base steel in the final performance of modified materials on the surface.

3.1. Deep rolling

Deep rolling is a process that uses mechanical work by plastic deformation to increase hardness and reduce surface roughness by introducing compressive residual stresses into components [36–38], [83–86]. In this process, a mechanically or hydraulically controlled sphere or roller scans the parts, applying a specific pressure on the surface of the component, Fig. 4, inducing plastic deformation on the surface and subsurface regions, by approximately 1–2 mm [87], [88].

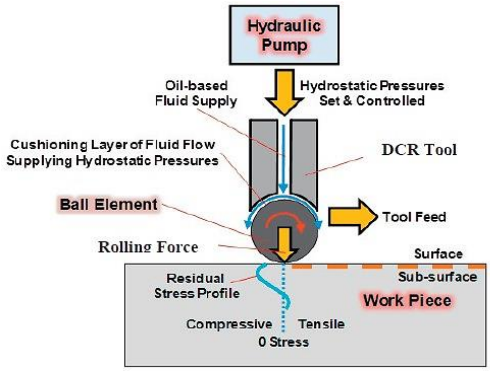

Fig. 4: Working Principles of Deep Rolling Process. Reproduced from [89].

Deep rolling can induce residual tensile and compressive stresses. This residual compression stresses result in parts with higher fatigue strength precisely because they inhibit the propagation of surface cracks. Due to these factors, deep rolling has been a desired alternative to increase residual stresses of compression on parts after the machining process [36–40], [84–86], [90].

Studies developed by Delgado et al. [88] show the influence of some parameters in the deep rolling process on the residual stresses. The main parameters that interfere with the process are speed, applied pressure, number of passes, ball and/or roller diameters and tool feed rate. The speed used depends on the sensitivity of the material to deformation and has a direct impact on hardness and roughness of the parts subjected to deep rolling [86]. Delgado et al. [88] state that the pressure applied in the deep rolling process should be sufficient to cause plastic deformation, and Grabe et al. [86] explain that increased pressure contributes to the reduction of surface roughness. Trauth et al. [91] observed that when the pressure exceeds a certain value, the material becomes overloaded and, according to Scheil et al. [92] starts to degrade.

In general, studies by Perenda et al. [93] confirm that the roughness tends to decrease after the deep rolling process. Prabhu et al. [94] analyzed the behavior of roughness values Ra varying some process parameters, among them the pressure and the number of passes. In their work, it was contacted that the increase in the number of passes reduces the value of Ra, while the increase of the pressure does not exert significant influence. Abrão et al. [37] showed that the number of passes has no significant influence on the residual stresses induced by deep rolling. On the other hand, Abrão et al. [38] conclude that the increase in the number of passes provides an increase in the hardness in the subsurface, due to the plastic deformation generated by the Hertzian contact pressure.

Results presented by Matlock et al. [39] and Richards et al. [40] show the importance of microstructure and base material properties in the subsequent response to surface modification by deep rolling. Three medium carbon bar steels with microstructures characteristic for forging steels of interest for crankshaft and other automotive applications, were investigated: a quenched and tempered steel with a heavily tempered martensitic microstructure; a non-traditional bainitic direct-cooled steel that contains 14.5 pct. retained austenite; and a hot rolled ferritic/pearlitic low alloy steel. A comparison of the deep rolled S-N data and the baseline data of bainitic direct-cooled steel NTB are shown in (Fig. 5). All three materials exhibited a significant increase (> 50%) in the endurance limit as a result of the deep rolling process.

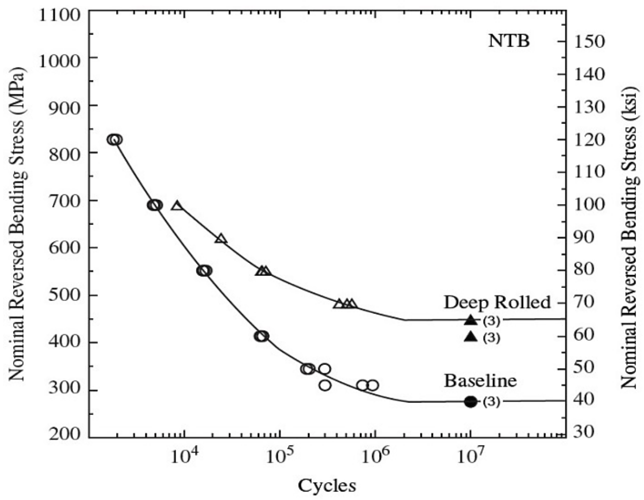

Fig. 5: A Comparison of Deep Rolling and Baseline Bending Fatigue Behavior for the Bainitic Direct-Cooled NTB. Reproduced from [39], [40].

For Matlock et al. [39] and Richards et al. [40] the response of the deep rolling will depend on the deformation behavior of the substrate. In this context, residual stresses and hardening may decrease over the life of the component, either by the effect of temperature or fatigue stresses and/or a combination of both [95–98]. In fact, the relationship between the properties of the materials as well as the parameters of deep rolling have not yet been fully explored and understood. This may be the reason why inconsistent results are often observed, especially with respect to the influence of the rolling parameters on the hardness distribution and surface finish [36], [38].

3.2. Plasma nitriding

Plasma nitriding is a diffusional process where the surface modification of components is carried out through the addition of nitrogen to improve the wear resistance and increase its lifespan, generating modified surface layers without dimensional changes of the final product [99]. There are two main mechanisms involved in surface hardening due to nitrogen diffusion: solid solution hardening and precipitation hardening. Since the nitrogen atoms are smaller than the ferritic matrix atoms, then the interstitial solid solution causes an increase in hardness. This increase in hardness is very small when compared to precipitation hardening. After the nitrogen saturation occurs in the matrix, it interacts with nitriding forming elements, such as iron or alloying elements, developing high hardness compounds. In commercial applications, the typical modified surface zone is up to 200–300 μm deep, rarely exceeding 600 μm [100].

During the plasma nitriding process a fine layer of compounds formed by iron nitrides ε($Fe_{2-3}N$) and/or γ'(Fe_4N) is produced on the surface of the samples, also a relatively thick diffusion zone just below the compound layer is formed [31], [33], [101], (Fig. 6). The chemical composition of the steel, the previous structure and the hardness of the core are extremely critical factors and influence the formation of the nitrided layers. Depending on the composition of the gas mixture, there may or may not be the formation of the compound layer [102], [103].

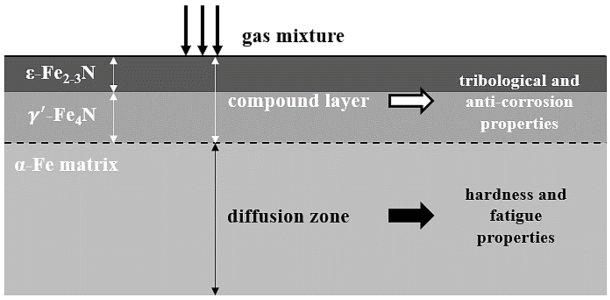

Fig. 6: Schematic Illustration of the Nitrided Zone of an Iron-Based Workpiece. The Nitrided Zone Can Be Subdivided Into the Compound Layer and Diffusion Zone. Reproduced from [101].

Both the compound layer and the diffusion zone depend on the process parameters (time, temperature, nitriding potential) and the diffusivity of the nitrogen, the latter being strongly influenced by the grain structure and composition of the materials [104–107]. The compound layer produced by the plasma nitriding process is responsible to improve the tribological and anticorrosive properties, while the diffusion zone determines the mechanical properties through the hardness and depth of the layer [108], [109]. For Podgornik et al. [31], the degree of improvement varies with the structure of the material, and with the distribution and residual stress levels. Therefore, for optimization of surface treatment, knowledge about the distribution and levels of residual stresses is essential.

The hardness of the compound layer is not affected by the carbide-forming elements (Al, Cr, Mo, Ti, V), since it is formed by nitrides of iron ε($Fe_{2-3}N$) and/or γ'(Fe_4N) [33], [103]. The gamma phase γ' (Fe_4N) usually formed with a gas mixture containing 15-30 wt.% nitrogen, has lower hardness and lower wear resistance, however, has a higher toughness and is recommended for applications in parts subject to high impact loads. The epsilon phase ε($Fe_{2-3}N$) developed with mixtures between 60-70 wt.% nitrogen, presents higher hardness and is better for applications in which good wear resistance and fatigue strength are desired, but does not have a good response to the impact [33].

It is already known that the aggregate properties of nitrided components are determined by both the core strength, structural characteristics of the compound layer and the diffusion zone [110]. Therefore, IWT researchers from Bremen systematically evaluated the behavior of bainitic steels 7MnB8 and 18MnCrSiMoS64 in the nitriding processes in comparison to conventional (ferritic-perlitic) steels 44SMn28 and 16MnCrS5Pb. Regular and compact layers of approximately 8 μm in thickness were obtained after nitriding of the selected steel grades [16].

In the process of plasma nitriding, it is possible to control the formation of the diffused layer, developing good hardness and toughness (even without formation of the compound layer), being recommended for situations where the material undergoes dynamic requests and high compressive stresses, hardness, friction wear and corrosion strength [111]. Other authors show that plasma surface treatments can favor fatigue life, because it inserts compressive stresses on the surface of the material, making it difficult to nucleate and propagate cracks [101], [112], [113]. In this context, Abdalla et al. [20] verified an increase in fatigue life of 300 M steel (with bainitic structure) after plasma nitriding. (Fig. 7) shows three fatigue curves (S-N) of 300 M steel (already bainitic) subjected to thermochemical treatments of laser carburizing and plasma nitriding. The fatigue performance of the steel subjected to the laser carburizing treatment was inferior to the steel with a bainitic structure, however, the hardness of the laser carburizing region was similar to that observed in the bainitic structure and did not contribute to delay the appearance of superficial microcracks. There was also an increase in surface roughness, a factor that contributed to decrease performance in fatigue [21].

In general, the increased fatigue strength of steels after plasma nitriding process is attributed to the increase of surface hardness, residual stress distribution and case depth. In the case of the high-cycle fatigue of quenched and tempered materials, fatigue crack usually initiates from the surface while in surface hardened materials crack initiation site shifts from the surface to subsurface region [16], [103], [108], [114–116]. Well-nitridable steels contain nitride-forming elements including 1-3 wt.% chromium, 0.2-0.5 wt.% molybdenum as well as smaller amounts of vanadium or niobium [117]. Those steels also have superior mechanical properties such as yield strength and toughness [32], [35], [117].

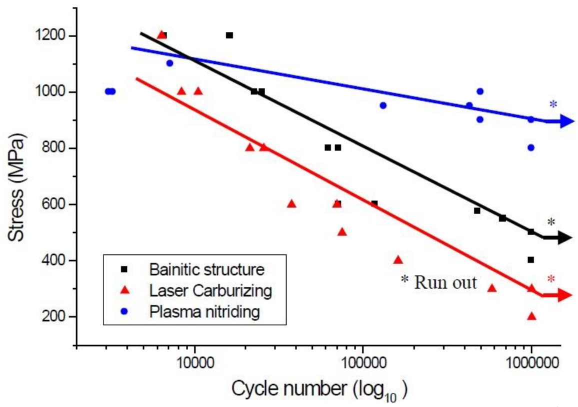

Fig. 7: Fatigue Curves (S-N) for the Conditions: 300 M Steel with Bainitic Structure and Steel with Surface Treatment of Plasma Nitriding and Laser Carburizing. Reproduced from [20].

Even though plasma nitriding treatment is a well-established method for improving the wear performance of steels and tools [28], [30], [118], [119], understanding the fracture properties of these hardened surfaces is far from complete [120]. The nitride phases that arise in the surface treatments have substantially lower fracture toughness than the underlying substrate [120], and this may adversely affect the wear performance of components such as gears that are subjected to severe service environments involving high mechanical stress loads and alternate loads [121–123].

4. Future developments and possibilities

As the conventional automotive component manufacturing chain usually consists of a long sequence of processes, different processing alternatives may be applied depending on the product specifications and their applications. For maximum improvement in fatigue and wear performance, surface modification techniques must be carefully controlled and combined with material of interest to ensure that undesirable characteristics are not introduced during the manufacturing of the components [25], [39], [124].
The combination of multiphase microstructures in steel opens a new range of possibilities, allowing to adjust levels of strength and ductility [14], [16], [20], [56], [61], [64]. The development of processes based on the use of continuous cooling bainitic steels for the forging can be an excellent alternative to replace the conventional quenching and tempering treatment with considerable reduction of the energy consumption, since it is not necessary to reheat the material for quenching nor for the tempering [3], [13].
In order to obtain high performance components, it is verified that there is great potential for the implementation of deep rolling before to plasma nitriding. By combining these surface hardening techniques, it is possible to increase the lifespan of mechanical components, provide surfaces with higher resistance to wear, corrosion and fatigue, and reduce the coefficient of friction. Previous work by [118], [125] point out that the previous superficial state of substrates subjected to plasma nitriding treatments has a direct influence on the formation of nitrided layers. This shows that the deep rolling process combined with nitriding can be more effective than just the nitriding process [126].

Acknowledgements

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References

[1] Capuano, L. Available online: https://www.eia.gov/pressroom/presentations/capuano_07242018.pdf (accessed on 10 March 2019).
[2] Hatwig, R. A.; Heck, N. C. ; Rocha, A. S. Novos aços bainíticos para forjamento. In International Forging Conference (SENAFOR), Porto Alegre, Brasil, 2016. (in Portuguese)
[3] Bhadeshia, H. K. D. H. Bainite in steels: theory and practice, 3rd ed.; Maney Publisching: Cambridge, 2015.
[4] Raedt, H.-W.; Speckenheuer, U.; Vollrath, K. New forged steels: energy-efficient solutions for stronger parts. ATZ autotechnology. 2012, 12, 12–17. https://doi.org/10.1365/s35595-012-0089-9.
[5] Buchmayr, B. Critical assessment 22: bainitic forging steels. Mater. Sci. Technol. 2016, 32, 517–522. https://doi.org/10.1080/02670836.2015.1114272.
[6] Bleck, W.; Prahl, U.; Hirt, G.; Bambach, M. Designing new forging steels by ICMPE. In Advances in Production Technology, ed. C. Brecher; Springer: Cham Heidelberg, 2015; Chap. 7, pp. 85–98. https://doi.org/10.1007/978-3-319-12304-2_7.
[7] Wang, J.; van der Wolk, P. J.; van der Zwaag, S. On the influence of alloying elements on the bainita reaction in low alloy steels during continuous cooling. J. Mater. Sci. 2000, 35, 4393–4404. https://doi.org/10.1023/A:1004865209116.
[8] Caballero, F. G.; Bhadeshia, H. K. D. H.; Mawella, K. J. A.; Jones, D. G.; Brown, P. Design of novel high strength bainitic steels: Part 2. Mater. Sci. Technol. 2001, 17, 517–522. https://doi.org/10.1179/026708301101510357.
[9] Caballero, F. G.; Garcia-Mateo, C.; Miller, M. K. Modern steels at atomic and nanometer scales. Mater. Sci. Technol. 2014, 31, 764–772. https://doi.org/10.1179/1743284714Y.0000000685.
[10] Rose, A. J.; Mohammed, F.; Smith, A. W. F.; Davies, P. A.; Clarke, R. D. Superbainite: laboratory concept to commercial product. Mater. Sci. Technol., 2014, 30, 1094–1098. https://doi.org/10.1179/1743284714Y.0000000504.
[11] Garbarz, B.; Marcisz, J.; Burian, W. Technological peculiarities of manufacturing nanobainitic steel plates. In METEC and 2nd ESTAD Conf., Düsseldorf, 2015.

[12] Fischer, M.; Henning, H.-H.; Bleck, W.; Huskic, A.; Kazhai, M.; Hadifi, T.; Bouguecha, A.; Behrens, B.-A. EcoForge: Enerigeeffiziente Prozesskette zur Herstellung von HochleistungsSchmiedebauteilen. J. Heat Treat. Mater. 2014, 69, 209–219. (in German) https://doi.org/10.3139/105.110220.
[13] Keul, C.; Wirths, V.; Bleck, W. New bainitic steel for forgings. Arch. Civ. Mech. Eng. 2012, 12, 119–125. https://doi.org/10.1016/j.acme.2012.04.012.
[14] Zajac, S.; Komenda, J.; Morris, P.; Dierickx, P.; Matera, S.; Penalba Diaz, F. Quantitative structure–property relationship for complex bainitic microstructures. In Technical Steel Research report no. EUR 21245EN. European Commission, Luxembourg, 2005.
[15] Luo, Y.; Peng, J.; Wang, H.; Wu, X. Effect of tempering on microstructure and mechanical properties of a non-quenched bainitic steel. Mater. Sci. Eng. A. 2010, 527, 3433–3437. https://doi.org/10.1016/j.msea.2010.02.010.
[16] Lembke, M. I.; Olschewki, G.; Roelofs, H.; Klümper-Westkamp, H. Nitrieren von hochfesten, bainitischen langprodukten. J. Heat Treat. Mat. 2014, 69, 195–200. (in German) https://doi.org/10.3139/105.110226.
[17] Merkel, C.; Engineer, J. Hochfester bainitischer stahl 20MnCrMo7 für umformanwendungen. Schmiede Journal. 2014, 38–41. (in German)
[18] Bruchwald, O.; Frackowiak, W.; Bucquet, T.; Huskic, A.; Reimche, W.; Maier, H. J. In-situ-erfassung der werkstoffumwandlung und gefügeausbildung von schmiedebauteilen im abkühlpfad. J. Heat Treat. Mat. 2015, 70, 150–161. (in German) https://doi.org/10.3139/105.110259.
[19] Roelofs, H.; Hasler, St.; Urlau, U.; Lembke, M. I.; Olschewski, G. Continuously cooled bainitic steel HSX®Z12: one decade of experience. In International Conference on Steels in Cars and Trucks, Braunschweig, Germany, 2014.
[20] Abdalla, A. J.; Santos, D.; Vasconcelos, G.; Baggio-Scheid, V. H.; Silva, D. F. Changing in fatigue life of 300 M bainitic steel afeter laser carburizing and plasma nitriding. In International Fatigue Congress (MATEC Web of Conferences), 2018. https://doi.org/10.1051/matecconf/201816521002.
[21] Genel, K.; Demirkol, M.; Çapa, M. Effect of ion nitriding on fatigue behavior of AISI 4140 steel. Mater. Sci. Eng. A. 2000, 279, 207–216. https://doi.org/10.1016/S0921-5093(99)00689-9.
[22] Suh, C. M.; Hwang, J. K.; Son, K. S.; Jang, H. K. Fatigue characteristics of nitrided SACM 645 according to the nitriding condition and notch. Mater. Sci. Eng. A. 2005, 392, 31–37. https://doi.org/10.1016/j.msea.2004.07.066.
[23] Zhang, P.; Zhang, F. C.; Yan, Z. G.; Wang, T. S.; Qian, L. H. Wear property of low temperature bainite in the surface layer of a carburized low carbon steel. Wear. 2011, 271, 697–704. https://doi.org/10.1016/j.wear.2010.12.025.
[24] Rakhit, A. K. Heat treatment of gears: a practical guide to engineers; ASM International: Materials Park, 2000.
[25] Davis, J. R. Gear materials, properties, and manufacture; ASM International: Materials Park, 2005.
[26] Leitão, C. J.; Mei, P. R.; Libardi, R. Efeitos da cementação e da nitretação no custo e na qualidade de engrenagens produzidas com aços ABNT 4140 e 8620. Tecnologia em Metalurgia, Materiais e Mineração. 2012, 9, 257–263. (in Portuguese) https://doi.org/10.4322/tmm.2012.036.
[27] Rego, R.; Löpenhaus, C.; Gomes, J.; Klocke, F. Residual stress interaction on gear manufacturing. J. Mater. Process. Technol. 2018, 252, 249–258. https://doi.org/10.1016/j.jmatprotec.2017.09.017.
[28] Skonieski, A. F. O.; Lima, E. S.; Hirsch, T.; Rocha, A. S. Heterogeneidade de temperaturas em fornos de nitretação a plasma. Estudos Tecnológicos. 2008, 4, 37–43. (in Portuguese)
[29] Leskovsek, V.; Podgornik, B.; Nolan, D. Modelling of residual stress profiles in plasma nitrided tool steel. Mater. Charact. 2008, 59, 454–461. https://doi.org/10.1016/j.matchar.2007.03.009.
[30] Ochao, E. A.; Wisnivesky, D.; Minea, T.; Ganciu, M.; Tauziede, C.; Chapon, P.; Alvarez, F. Microstructure and properties of the compound layer obtained by pulsed plasma nitriding in steel gears. Surf. Coat. Technol. 2009, 203, 1457–1461. https://doi.org/10.1016/j.surfcoat.2008.11.025.
[31] Podgornik, B.; Leskovsek, V.; Kovacic, M.; Vizintin, J. Analysis and prediction of residual stresses in nitrided tool steel. Mater. Sci. Forum, 2011, 681, 352–357. https://doi.org/10.4028/www.scientific.net/MSF.681.352.
[32] Rolinski, E. Deep nitriding for gear applications and their partial treatments: plasma/ion nitriding meets demanding gear applications by increase load capacity of gears and increased fatigue strength of components as well as less complicated masking treatments. In Gears Solutions, 2016.
[33] Silva, A. L. V. C.; Mei, P. R. Aços e ligas especiais. 2nd ed.; Edgard Blücher: São Paulo, 2006. (in Portuguese)
[34] Chiaverini, V. Tratamento térmico das ligas metálicas. 1st ed.; Associação Brasileira de Metalurgia e Materiais: São Paulo, 2008. (in Portuguese)
[35] Hoja, S.; Hoffmann, F.; Zoch, H.-W.; Schurer, S.; Tobie, T.; Stahl, K. Design of deep nitriding treatments for gears. J. Heat Treat. Mat. 2015, 70, 276–285. https://doi.org/10.3139/105.110271.
[36] Abrão, A. M.; Denkena, B.; Köhler, J.; Breidenstein, B.; Mörke, T.; Rodrigues, P. C. M. The influence of heat treatment and deep rolling on the mechanical properties and integrity of AISI 1060 steel. J. Mater. Process. Technol. 2014, 21, 3020–3030. https://doi.org/10.1016/j.jmatprotec.2014.07.013.
[37] Abrão, A. M.; Denkena, B.; Breidenstein, B.; Mörke, T. Surface and subsurface alterations induced by deep rolling of hardened AISI 1060 steel. Production Engineering. 2014, 8, 551–558. https://doi.org/10.1007/s11740-014-0539-x.
[38] Abrão, A. M.; Denkena, B.; Köhler, J.; Breidenstein, B.; Mörke, T. The influence of deep rolling on the surface integrity of AISI 1060 high carbon steel. Procedia CIRP. 2014, 13, 31–36. https://doi.org/10.1016/j.procir.2014.04.006.
[39] Matlock, D. K.; Alogab, K. A.; Richards, M. D.; Speer, J. G. Surface processing to improve the fatigue resistance of advanced bar steels for automotive applications. Materials Research. 2005, 453-459. https://doi.org/10.1590/S1516-14392005000400017.
[40] Richards, M. D.; Matlock, D. K.; Speer, J. G. Deep rolling response of notched medium carbon bar steels. In SAE Technical Publication, no. 2004-01-1528. SAE International, Warrendale, PA, 2004. https://doi.org/10.4271/2004-01-1528.
[41] SSAB Tunnplat. Sheet steel handbook: design and fabrication in high strength sheet steel; SSAB Tunnplat AB: Sweden, 1996.
[42] SSAB Tunnplat. Sheet steel forming handbook: size shearing and plastic forming; SSAB Tunnplat AB: Sweden, 1998.
[43] SSAB Tunnplat. Sheet steel joining handbook: joining of high strength steels; SSAB Tunnplat AB: Sweden, 2004.
[44] Davies, G. Materials for automotive bodies. Elsevier: Butterworth Heinemann, 2012.
[45] Verlinden, B.; Driver, J.; Samajdar, I.; Doherty, R. D. Thermo-mechanical processing of metallic materials. 1st ed.; Elsevier: Amsterdam, 2007.
[46] Nanda, T.; Singh, V.; Singh, V.; Chakraborty, A.; Sharma, S. Third generation of advanced high-strength steels: processing routes and properties. Journal of Materials: Design and Applications. 2016, 1–30.
[47] Gladman, T. The physical metallurgy of microalloyed steels. 1st ed.; Institute of Materials: London, 1997.
[48] Bhadeshia, H. K. D. H.; Honeycombe, R. W. K. Steel: microstructure and properties. 3rd ed.; Elsevier: Cambridge, 2006.
[49] DeGarmo, E. P.; Black, J. T.; Kohser, R. A. Materials and process in manufacturing. 9th ed.; Wiley, 2003.
[50] Zhao, J.; Jiang, Z. Thermomechanical processing of advanced high strength steels. Prog. Mater. Sci. 2018, 94, 174–242. https://doi.org/10.1016/j.pmatsci.2018.01.006.
[51] Ghosh, A.; Das, S.; Chatterjee, S.; Mishra, B.; Rao, P. R. Influence of thermo-mechanical processing and different post-cooling techniques on structure and properties of an ultra-low carbon Cu bearing HSLA forging. Mater. Sci. Eng. A. 2003, 348, 299-308. https://doi.org/10.1016/S0921-5093(02)00735-9.
[52] Militzer, M. Comprehensive materials processing. In Thermomechanical processed steels. Elsevier: Vancouver, 2014. Volume 1, pp. 191–216. https://doi.org/10.1016/B978-0-08-096532-1.00115-1.
[53] Tamura, I.; Sekine, H.; Tanaka, T.; Ouchi, C. Thermomechanical processing of high-strength low-alloy steels. Butterworth: London, 1988.
[54] Maity, S. K.; Ballal, N. B.; Kawalla, R. Development of process for thermomechanical treatment of ultrahigh strength steel prepared by electroslag refining. Ironmaking & Steelmaking. 2007, 34, 332–342. https://doi.org/10.1179/174328107X168156.
[55] Hasler, S.; Roelofs, H.; Lembke, M.; Caballero, F.G. New air-cooled steels with outstanding impact toughness. In International Conference on Steels in Cars and Trucks. Salzburg, 2011.
[56] Eggbauer, G.; Buchmayr, B. High-strength bainitic steels for forged products. Springer-Verlag Wien, 2015, 160, 209–213. https://doi.org/10.1007/s00501-015-0351-8.

[57] Caballero, F. G.; Santofimia, M. J.; García-Mateo, C.; Chao, J.; Garcia De Andres, C. Theoretical design and advanced microstructure in super high strength steels. Mater. Des. 2009, 30, 2077–2083. https://doi.org/10.1016/j.matdes.2008.08.042.
[58] He, J.; Zhao, A.; Huang, Y.; Zhi, C.; Zhao, F. Acceleration of bainite transformation at low temperature by warm rolling process. Materials Today: Proceedings. 2015, 2, 289–294. https://doi.org/10.1016/j.matpr.2015.05.040.
[59] Zhenyao, S.; Zhichao, W.; Zhuang, L.; Shuai, W.; Jijie, W. Effect of thermomechanical processing on the microstructure and mechanical properties of low carbon steel. In International Conference on Advanced Design and Manufacturing Engineering, 1984–1989, 2015.
[60] Zhao, J.; Jiang, Z. Rolling of advanced high strength steels: theory, simulation and practice. CRC Press: Australia, 2017. https://doi.org/10.1201/9781315120577.
[61] Caballero, F. G.; Roelofs, H.; Hasler, St.; Capdevila, C.; Chao, J.; Cornide, J.; Garcia-Mateo, C. Influence of bainite morphology on impact toughness of continuously cooled cementite free bainitic steels. Mater. Sci. Technol. 2012, 28, 95–102. https://doi.org/10.1179/1743284710Y.0000000047.
[62] Eggbauer, G.; Weber, A.; Lechleitner, J.; Buchmayr, B. Charakterisierung bainitischer gefügezustände in schmiedestählen. Berg-und Hüttenmännische Monatshefte. 2014, 159, 194–200. (in German) https://doi.org/10.1007/s00501-014-0244-2.
[63] Wirths, V.; Wagener, R.; Bleck, W.; Melz, T. Bainitic forging steels for cyclic loading. Adv. Mater. Res. 2014, 922, 813–818. https://doi.org/10.4028/www.scientific.net/AMR.922.813.
[64] Sourmail, T.; Smanio, V.; Ziegler, C.; Heuer, V.; Kuntz, M.; Caballero, F. G.; Garcia-Mateo, C.; Cornide, J.; Elvira, R.; Leiro, A.; Vuorinen, E.; Teeri, T. Novel nanostructured bainitic steel grades to answer the need for high-performance steel components (NANOBAIN). In Research Fund for Coal and Steel Publications. European Commission, 2013.
[65] Caballero, F. G.; Santofimia, M. J.; Capdevila, C.; García-Mateo, C.; Garcia De Andres, C. Design of advanced bainitic steels by optimization of TTT diagrams and T0 curves. ISIJ International. 2006, 46, 1479–1488. https://doi.org/10.2355/isijinternational.46.1479.
[66] Wirths, V.; Elek, L.; Bleck, W.; Wagener, R.; Melz, T. Karbidfreie bainitische schmiedestähle mit verbesserter betriebsfestigkeit. Schmiede Journal. 2015, 28–32. (in German)
[67] Terzic, A.; Calcagnotto, M.; Guk, S.; Schulz, T.; Kawalla, R. Influence of boron on transformation behavior during continuous cooling of low alloyed steels. Mat. Sci. Eng. A. 2013, 584, 32–40. https://doi.org/10.1016/j.msea.2013.07.010.
[68] Song, T.; Cooman, B. C. Effect of boron on the isothermal bainite transformation. Metall. Mater. Trans. A. 2013, 44, 1686–1705. https://doi.org/10.1007/s11661-012-1522-9.
[69] Caballero, F. G.; Bhadeshia, H. K. D. H.; Mawella, K. J. A.; Jones, D. G.; Brown, P. Design of novel high strength bainitic steels: Part 1. Mater. Sci. Technol. 2001, 17, 512–516. https://doi.org/10.1179/026708301101510348.
[70] Gomez, G.; Perez, T.; Bhadeshia, H. K. D. H. Air cooled bainitic steels for strong, seamless pipes. Part 1 – alloy design, kinetics and microstructure. Mater. Sci. Technol. 2009, 25, 1501–1507. https://doi.org/10.1179/174328408X388130.
[71] Gomez, G.; Perez, T.; Bhadeshia, H. K. D. H. Air cooled bainitic steels for strong, seamless pipes. Part 2 – properties and microstructure of rolled material. Mater. Sci. Technol. 2009, 25, 1508–1512. https://doi.org/10.1179/174328408X388149.
[72] Hasler, S. Bainitischer stahl swissbain-7MnB8 senkt herstellungskosten. Stahl Und Eisen. 2014, 134, 58–60. (in German)Engineer, S.; Merkel, C.; Wewers, B. EZM mark 20MnCrMo7 – ein neuer hochfester bainitischer stahl. In Product brochure, 2014. (in German)
[73] Caballero, F. G.; Capdevila, C.; Chao, J.; Cornide, J.; Garcia-Mateo, C.; Roelofs, H.; Hasler, S.; Mastrogiacomo, G. The Microstructure of continuously cooled tough bainitic steels. In International Conference on Super high strength steel, Peschiera, Italy, 2010.
[74] Khodabandeh, A. R.; Jahazi, M.; Yue, S. Aghdashi, S. T. The determination of optimum forging conditions for the production of high strength-high impact toughness automotive parts. Mater. Manuf. Process. 2006, 21, 105–110. https://doi.org/10.1080/AMP-20060666.
[75] Lemaitre, C.; Dierickx, P.; Bittes, G. Steels for high-performance diesel engines. Iron and Steel Technology. 2007, 4, 66–73.
[76] Garcia-Mateo, C.; Caballero, F. G. Ultra-high-strength bainitic steels. ISIJ International. 2005, 45, 1736–1740. https://doi.org/10.2355/isijinternational.45.1736.
[77] Timokhina, I. B.; Beladi, H.; Xiong, X. Y.; Adachi, Y.; Hodgson, P. D. Nanoscale microstructural characterization of a nanobainitc steel. Acta Mater. 2011, 59, 5511–5522. https://doi.org/10.1016/j.actamat.2011.05.024.
[78] Beladi, H.; Adachi, Y.; Timokhina, I.; Hodgson, P. D. Crystallographic analysis of nanobainitic steels. Scripta Mater. 2009, 60, 455–458. https://doi.org/10.1016/j.scriptamat.2008.11.030.
[79] Beladi, H.; Tari, V.; Timokhina, I. B.; Cizek, P.; Rohrer, G. S.; Rollett, A.; Hodgson, P. D. On the crystallographic characteristics of nanobainitic steel. Acta Mater. 2017, 127, 426–437. https://doi.org/10.1016/j.actamat.2017.01.058.
[80] Wang, T. S.; Yang, J.; Shang, C. J.; Li, X. Y.; Lv, B.; Zhang, M.; Zhang, F. C. Sliding friction surface microstructure and wear resistance of 9SiCr steel with low temperature austempering treatment. Surf. Coat. Technol. 2008, 202, 4036–4040. https://doi.org/10.1016/j.surfcoat.2008.02.013.
[81] Narayanaswamy, B.; Hodgson, P.; Timokhina, I.; Beladi, H. The impact of retained austenite characteristics on the two-body abrasive wear behavior of ultrahigh strength bainitic steels. Metall. Mater. Trans. A. 2016, 47, 4883–4895. https://doi.org/10.1007/s11661-016-3690-5.
[82] Fabijanic, D.; Timokhina, I.; Beladi, H.; Hodgson, P. The nitrocarburising response of low temperature bainite steel. Metals. 2017, 7, 1–8. https://doi.org/10.3390/met7070234.
[83] Groche, P.; Engels, M.; Steitz, M.; Mueller, C.; Scheil, J.; Heilmaier, M. Potential of mechanical surface treatment for mould and die production. Int. J. Mater. Res. 2012, 103, 783–789. https://doi.org/10.3139/146.110778.
[84] Abrão, A. M.; Denkena, B.; Köhler, J.; Breidenstein, B.; Mörke, T. The inducement of residual stress through deep rolling of AISI 1060 steel and its subsequent relaxation under cyclic loading. Int. J. Adv. Manufact. Technol. 2015, 79, 1939–1947. https://doi.org/10.1007/s00170-015-6946-0.
[85] Magalhães, F. C.; Abrão, A. M.; Denkena, B.; Breidenstein, B.; Mörke, T. Analytical modeling of surface roughness, hardness and residual stress induced by deep rolling. J. Mater. Eng. Perform. 2017, 26, 876–884. https://doi.org/10.1007/s11665-016-2486-5.
[86] Grabe, T. M.; Abrão, A. M.; Leal, C. A. A.; Denkena, B.; Breidenstein, B.; Meyer, K. Influência da operação de roleteamento sobre o acabamento e a resistência à fadiga do aço ABNT 4140. Acta Mechanìca et Mobilitatem. 2018, 3, 9–13. (in Portuguese)
[87] Klocke, F.; Mader, S. Fundamentals of the deep rolling of compressor blades for turbo aircraft engines. Steel Research International. 2005, 76, 229–235. https://doi.org/10.1002/srin.200506001.
[88] Delgado, P.; Cuesta, I. I.; Alegre, J. M.; Díaz, A. State of the art of deep rolling. Precision Engineering. 2016, 46, 1–10. https://doi.org/10.1016/j.precisioneng.2016.05.001.
[89] Wong, C. C.; Hartawan, A.; Teo, W. K. Deep cold rolling of features on aero-engine components. Procedia CIRP. 2014, 13, 350–354. https://doi.org/10.1016/j.procir.2014.04.059.
[90] Kloos, K. H.; Adelmann, J. Effect of deep rolling on fatigue properties of cast irons. J. Mechan. Beh. Mater. 1989, 2, 75–86. https://doi.org/10.1515/JMBM.1989.2.1-2.75.
[91] Trauth, D.; Klocke, F.; Mattfeld, P.; Klink, A. Time-efficient prediction of the surface layer state after deep rolling using similarity mechanics approach. Procedia CIRP. 2013, 9, 29–34. https://doi.org/10.1016/j.procir.2013.06.163.
[92] Scheil, J.; Müller, C.; Steitz, M.; Groche, P. Influence of process parameters on surface hardening in hammer peening and deep rolling. Key Engineering Materials. 2013, 554–557, 1819–1827. https://doi.org/10.4028/www.scientific.net/KEM.554-557.1819.
[93] Perenda, J.; Trajkovski, J.; Zerovnik, A.; Prebil, I. Residual stresses after deep rolling of a torsion bar made from high strength steel. J. Mater. Process. Technol. 2015, 218, 89–98. https://doi.org/10.1016/j.jmatprotec.2014.11.042
[94] Prabhu, P. R.; Kulkarni, S. M.; Sharma, S. S.; Jagannath, K.; Bhat, C. Deep cold rolling process on AISI 4140 steel and optimization of surface roughness by response surface methodology. In International Conference on Mechanical, Production and Materials Engineering, 2012.
[95] Michaud, H.; Sprauel, J. M.; Galzy, F. The residual stresses generated by deep rolling and their stability in fatigue & application to deep-rolled crankshafts. Mater. Sc. Forum. 2006, 524–525, 45–50. https://doi.org/10.4028/www.scientific.net/MSF.524-525.45.

[96] Juijerm, P.; Altenberger, I. Effect of temperature on cyclic deformation behavior and residual stress relaxation of deep rolled under-aged aluminium alloy AA6110. Mater. Sci. Eng. A. 2007, 452–453, 475–48. https://doi.org/10.1016/j.msea.2006.10.074.
[97] Juijerm, P.; Altenberger, I. Effective boundary of deep-rolling treatment and its correlation with residual stress stability of Al–Mg–Mn and Al–Mg–Si–Cu alloys. Scripta Mater. 2007, 56, 745–748. https://doi.org/10.1016/j.scriptamat.2007.01.021.
[98] Altenberger, I.; Nalla, R. K.; Sano, Y.; Wagner, L.; Ritchie, R. O. On the effect of deep-rolling and laser-peening on the stress-controlled low- and high-cycle fatigue behavior of Ti-6Al-4V at elevated temperatures up to 550 °C. Int. J. Fatigue. 2012, 44, 292–302. https://doi.org/10.1016/j.ijfatigue.2012.03.008.
[99] Suchentrunk, R.; Fuesser, H. J.; Staudigl, G.; Jonke, D.; Meyer, M. Plasma surface engineering - innovative processes and coating systems for hig https://doi.org/10.1016/S0257-8972(98)00833-0.h-quality products. Surf. Coat. Technol. 1999, 112, 351–357.
[100] Czerwinski, F. Thermochemical Treatment of Metals. In Heat Treatment - Conventional and Novel Applications. Intech: Canada, 2012. pp. 73–112. https://doi.org/10.5772/51566.
[101] Jung, K. S. Nitriding of iron-based ternary alloys: Fe-Cr-Ti and Fe-Cr-Al. Doctoral Thesis – Universität Stuttgart. Stuttgart, 2011.
[102] Karakan, M.; Alsaran, A.; Çelik, A. Effects of various gas mixtures on plasma nitriding behavior of AISI 5140 steel. Mater. Charact. 2003, 49, 241–246. https://doi.org/10.1016/S1044-5803(03)00010-X.
[103] Sirin, S. Y.; Sirin, K.; Kaluc, E. Effect of the ion nitriding surface hardening process on fatigue behavior of AISI 4340 steel. Mater. Charact. 2008, 59, 351–358. https://doi.org/10.1016/j.matchar.2007.01.019.
[104] Tong, W. P.; Tao, N. R.; Wang, Z. B.; Lu, J.; Lu, K. Nitriding iron at lower temperatures. Science. 2003, 299, 686–688. https://doi.org/10.1126/science.1080216.
[105] Tong, W. P.; Tao, N. R.; Wang, Z. B.; Zhang, H. W.; Lu, J.; Lu, K. The formation of ε-Fe3–2N phase in a nanocrystalline Fe. Scripta Mater. 2004, 50, 647–650. https://doi.org/10.1016/j.scriptamat.2003.11.022.
[106] Lin, Y.; Lu, J.; Wang, L.; Xu, T.; Xue, Q. Surface nanocrystallization by surface mechanical attrition treatment and its effect on structure and properties of plasma nitrided AISI 321 stainless steel. Acta Mater. 2006, 54, 5599–5605. https://doi.org/10.1016/j.actamat.2006.08.014.
[107] Tong, W. P.; Han, Z.; Wang, L. M.; Lu, J.; Lu, K. Low-temperature nitriding of 38CrMoAl steel with a nanostructured surface layer induced by surface mechanical attrition treatment. Surf. Coat. Technol. 2008, 202, 4957–4963. https://doi.org/10.1016/j.surfcoat.2008.04.085.
[108] Bell, T.; Loh, N. L. The fatigue characteristics of plasma nitrided three pct Cr–Mo steel. J. Heat Treat. 1982, 2, 232–237. https://doi.org/10.1007/BF02833223.
[109] Leppänen, R.; Johnsson, H. Properties of nitride components: a result of the material and the nitriding process. In Technical Report No. 1. Ovako Steel: Sweden, 1999.
[110] Ashrafizadeh, F. Influence of plasma and gas nitriding on fatigue resistance of plain carbon (CK45) steel. Surf. Coat. Technol. 2003, 173/174, 1196–120. https://doi.org/10.1016/S0257-8972(03)00460-2.
[111] Chang, D. Y.; Lee, S. Y.; Kang, S. G. Effect of plasma nitriding on the surface properties of the chromium diffusion coating layer in iron-base alloys. Surf. Coat. Technol. 1999, 116/119, 391–397. https://doi.org/10.1016/S0257-8972(99)00234-0
[112] Okamoto, A.; Nakamura, H. The influence of residual stress on fatigue cracking. J. Pressure Vessel Technol. 1990, 112, 199–203. https://doi.org/10.1115/1.2928614.
[113] Nicoletto, G.; Tucci, A.; Esposito, L. Sliding wear behavior of nitride and nitrocarburized cast irons. Wear, 1996, 197, 38–44. https://doi.org/10.1016/0043-1648(95)06753-1.
[114] Sun, Y.; Bell, T. Plasma surface engineering of low alloy steel. Mater. Sci. Eng. A. 1991, 140, 419–434. https://doi.org/10.1016/0921-5093(91)90458-Y.
[115] Tosic, M. M.; Terzic, I.; Gligorijevic, R.; Ognjanovic, M. Fatigue improvements of glow-discharge-plasma-nitrided steel rotary specimens. Surf. Coat. Technol. 1994, 63, 73–83. https://doi.org/10.1016/S0257-8972(05)80010-6.
[116] Hussain, K.; Tauqir, A.; Haq, A. U, Khan, A. Q. Influence of gas nitriding on fatigue resistance of maraging steel. Int. J. Fatigue. 1999, 21, 163–168. https://doi.org/10.1016/S0142-1123(98)00063-2.
[117] Rolinski, E.; Leclaire, F.; Clubine, D.; Sharp, G.; Boyer, D.; Notman, R. Kinetics of plasma nitriding and renitriding of 3% Cr-Mo-V steel. J. Mater. Eng. Perform. 2000, 9, 457–462. https://doi.org/10.1361/105994900770345863.
[118] Rocha, A. S.; Strohaecker, T.; Hirsch, T. Effect of different surface states before plasma nitriding on properties and machining behavior of M2 high-speed steel. Surf. Coat. Technol. 2003, 165, 176–185. https://doi.org/10.1016/S0257-8972(02)00768-5.
[119] Both, G. B.; Rocha, A. S.; Santos, G. R.; Hirsch, T. K. An investigation on the suitability of different surface treatments applied to a DIN X100CrMoV8-1-1 for cold forming applications. Surf. Coat. Technol. 2014, 244, 142–150. https://doi.org/10.1016/j.surfcoat.2014.01.060.
[120] Nolan, D.; Leskovsek, V.; Jenko, M. Estimation of fracture toughness of nitride compound layer on tool steel by application of the Vickers indentation method. Surf. Coat. Technol. 2006, 201, 182–188. https://doi.org/10.1016/j.surfcoat.2005.11.077.
[121] Batista, A. C.; Dias, A. M.; Lebrun, J. L.; Le Flour, J. C.; Inglebert, G. Contact fatigue of automotive gears: evolution and effects of residual stresses introduced by surface treatments. Fatigue Fract. Eng. Mater. Struct. 2000, 23, 217–228. https://doi.org/10.1046/j.1460-2695.2000.00268.x.
[122] Li, W.; Liu, B. Experimental investigation on the effect of shot peening on contact fatigue strength for carburized and quenched gears. Int. J. Fatigue. 2018, 106, 103–113. https://doi.org/10.1016/j.ijfatigue.2017.09.015.
[123] Terrin, A.; Dengo, C.; Meneghetti, G. Experimental analysis of contact fatigue damage in case hardened gears for off-highway axles. Eng. Fail. Anal. 2017, 76, 10–26. https://doi.org/10.1016/j.engfailanal.2017.01.019.
[124] Boniardi, M.; D'errico, F.; Tagliabue, C. Influence of carburizing and nitriding on failure of gears – A case study. Eng. Fail. Anal. 2006, 13, 312–339. https://doi.org/10.1016/j.engfailanal.2005.02.021.
[125] Gao, Y. Influence of deep-nitriding and shot peening on rolling contact fatigue performance of 32Cr3MoVA steel. J. Mater. Eng. Perform. 2008, 17, 455–459. https://doi.org/10.1007/s11665-007-9155-7.
[126] Tadi, A. J.; Hosseini, S. R.; Semiromi, M. N. Influence of surface nano/ultrafine formed via pre-deep rolling process on the plasma nitriding characteristics of the AISI 316L stainless steel. Int. Nano Letters. 2017, 7, 217–223. https://doi.org/10.1007/s40089-017-0218-y.