Mechanical properties of ausforged 27MnSiVS6 microalloyed steel

Propriedades mecânicas do aço microligado 27MnSiVS6 ausforjado

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Resumo

Os processos de forjamento a quente aplicados aos aços microligados, também conhecidos como aços de alta resistência e baixa liga (ARBL), têm uma extensa aplicação na produção de componentes automotivos. O objetivo desse trabalho foi o de estudar o comportamento microestrutural por microscopia óptica e o comportamento mecânico, em termos de propriedades de resistência e tenacidade do aço microligado 27MnSiVS6, quando empregado no processo denominado "ausforging", a fim de se analisarem o desempenho do processo e a qualidade dos produtos, comparando-os com os processos de forjamento a quente e a morno. Os produtos forjados provenientes do "ausforging" que foram submetidos aos ensaios de tração unidirecional, fadiga em flexão rotativa e tenacidade à fratura, apresentaram as melhores propriedades mecânicas. Os testes estatísticos aplicados aos resultados permitiram concluir que os produtos obtidos por "ausforging" apresentaram a melhor combinação de resistência mecânica e qualidade superficial dos produtos forjados, sem aumentar a carga de forjamento.

Palavras-chave: "Ausforging", forjamento, metalurgia física.

Abstract

Hot forging of microalloyed steels, also known as high strength low alloy steels (HSLA), has a wide application for manufacturing automotive components. The purpose of this study was to evaluate the microstructure and the mechanical strength and toughness of the 27MnSiVS6 microalloyed steel, when formed by ausforging, to analyze the process performance and the quality of products. Ausforging was compared to both hot and warm forging processes. As a result, considering the tensile, fatigue (under rotating bending) and the fracture toughness tests, the best mechanical properties were shown by the ausforged products. Statistical analyses revealed that products obtained by ausforging presented the best combination of strength and surface quality, without increasing the forging load.

Keywords: *Ausforging, forging, physical metallurgy.*

1. Introduction

Warm forging is widely used in automotive industries (Xinbo et al., 2003). The temperatures for warm forging steels range from 600 to 900°C and offer some important advantages compared to traditional forging processes. Warm forged products show better dimensional accuracy and better surface quality, if compared to hot forgings because of the smaller oxidation and expansion/ contraction of the material and forging dies (García-Mateo et al., 2001).

Hot forging is a classic and also widely diffused industrial process. Every year in Europe, millions of tons of steel parts are produced by hot forging processes (Panjan et al., 2002). For a good combination of toughness and strength, forging processes provide a microstructure of fine grains (Bakkaloglu, 2002; Li et al., 2012).

The term ausforming, originating from the technology of high strength steels (Franz and Hornbogen, 1998), is a thermomechanical treatment used to improve the microstructure and mechanical properties in terms of strength and toughness of high-alloy steels (Franz and Hornbogen, 1998; Isogawa et al., 1998; Hornbogen, 1999). Otherwise ausforging consists in heating the material until the austenitization temperature is reached. Subsequently, the material is cooled to a temperature range where the austenite will be metastable, in which the material will be forged (Bakkaloglu, 2002).

The alloy properties are strongly influenced by refining the grain. The benefits of this practice are the improvement of the fracture resistance of steels and the super elasticity phenomenon, which can be achieved in materials with grain size smaller than 10 mm (Humphreys et al., 2001). The grain refinement can be done directly during casting by the solidification control or by variations in the chemical composition of steels followed by suitable thermomechanical processes. Microalloyed steels are obtained with little addition of microalloying elements, which are considered very important structural materials. Among many factors that stimulated the development of the HSLA steel technology, there are the reduction of the structural weight and fabrication cost (Sun et al., 2012; Dong, 2012) and the ability of microalloying elements to produce a substantial grain refinement and strengthening by precipitation (Kuziak et al., 1995).

The reason for studying the ausforging process was motivated by the need to produce semi-finished products with well-defined mechanical properties such as strength and toughness. The decrease of the energy used to deform and the increase of forgeability are also reasons that justify this study. Therefore, the aim of this study was to evaluate the microstructure and the mechanical strength and toughness of the 27MnSiVS6 microalloyed steel, when ausforged, as well as to analyze the process performance and the quality of products by comparing to those obtained by hot and warm forging.

2. Material and methods

The material used in this study was a vanadium microalloyed steel with a little addition of titanium, which is employed in the automotive components industry. The steel was in the normalized metallurgical condition, and its chemical composition is presented in Table 1.

Figure 1 shows the geometry and dimensions of the initial billet and also the dimensions and geometry of the forged component. Forging tests were held in warm, hot and ausforging conditions as defined in Table 2. The billets were kept at the heating temperature for 15 minutes (soaking time) and the forging dies were pre-heated to 180°C.

A visual analysis was performed on forged products of the studied processes

C	Si	Mn	P	S	Cr	Mo	Ni	Al	Cu	N	Ti	V
0.310	0.687	1.463	0.010	0.056	0.181	0.006	0.089	0.016	0.016	0.016	0.018	0.111

Table 1
Chemical composition of the 27MnSiVS6 microalloyed steel (weight %).

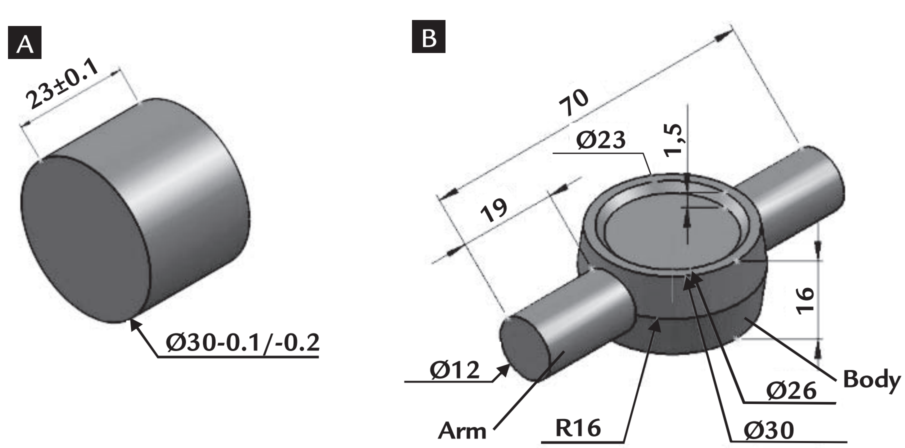

Figure 1
(A) Billet
(B) Forged product.

Process	Heating temperature	Cooling rate before forging	Forging temperature
Hot forging	1150°C	none	1150°C
Warm forging	800°C	none	800°C
Ausforging	1150°C	8.7°C/s	800°C

Table 2
Forging tests conditions.

and consisted in observing whether the product had completely filled the forging dies or not. The process which best completed the dies and showed minor surface defects was characterized as presenting the best forgeability.

Tensile test specimens were prepared according to the standard ASTM E8: 2001. The fatigue test (rotating bending) was conducted at a frequency of 83 Hz and all experiments were limited to five million cycles with samples prepared as defined by the standard ASTM E466: 2002. The CTOD values were determined by the fracture toughness tests which characterize the material resistance to the crack propagation (Hertzberg, 1989). The fracture toughness parameter used in this study was the displacement of the opening crack tip, defined by the maximum load (d_m). Images of the microstructure in the body region and in the arms region at transverse and longitudinal directions of the product, were obtained to characterize the mean ferrite grains (Figure 1). The method used to determine the mean ferrite grain size was the Heyn Linear Intercept Procedure, according standard ABNT NBR 11568.

Thirteen replicates were used in each sample of forging tests, while in the tensile tests, three replicates for each sample. In the fatigue and fracture toughness tests samples with five replicates were used for each test. Finally, two replicates were used for each sample in the metallographic analysis. Statistical analyses of mean contrasts were done with 95% confidence level (Montgomery, 1991).

3. Results

Forging tests

The curves with mean values of forging loads are shown in Figure 2. As a result, it was graphically observed that the lowest load was obtained with hot forging (305.5 ± 25.6 kN), followed by ausforging (559.28 ±28.7 kN). Also, the greatest load was observed for warm forging (582.25 ± 25.6 kN). However, after statistical analysis, only hot forging showed the lower mean in comparison to the two other processes. Therefore, the maximum mean loads of ausforging and warm forging were statistically similar.

A surface defect due to incorrect die filling occurred in the body and arms of the hot forged products. The same defect was also observed in the warm forged products. Ausforging was the only process which did not present any defect of die fulfillment. Therefore, ausforging proved to be the most appropriated process in comparison to both other processes, showing better forgeability.

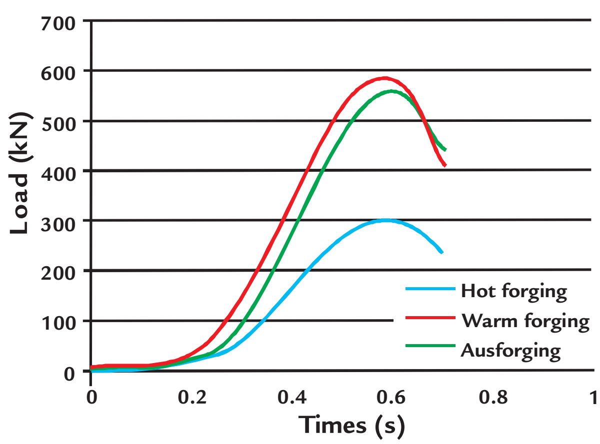

Figure 2
Forging load versus stroke time – mean values.

Mechanical properties

The mean mechanical properties obtained in the tensile tests are presented in Table 3.

The mean of the ultimate tensile strength (UTS) of ausforging was statistically higher than the other forging processes' means analyzed in this study. Also, the mean of hot forging was statistically higher than the warm process. It was found that the mean of the maximum yield strength (YS) for the hot process was statistically higher than the observed for warm forging. The mean of the percent elongation of the hot forging and ausforging were statistically similar, as well as they were lower in comparison with the value obtained in the warm process.

A maximum stress of 474 MPa was applied in fatigue tests to favor the failure of specimens obtained by hot forging. The results of the fatigue test for all process are presented in Table 4.

Regarding all fracture toughness tests, the fracture of the specimens was not brittle, and all samples presented permanent strains. The results of CTOD

Table 3
Mechanical properties from tensile test.

Process	Yield Strength ± Standard Deviation (MPa)		Ultimate Strength Tensile ± Standard Deviation (MPa)		Elongation ± Standard Deviation (%)	
Hot forging	648.06	± 7.33	892.63	± 13.17	16.03	± 0.73
Warm forging	591.76	± 6.34	803.92	± 16.98	20.42	± 0.44
Ausforging	720.38	± 6.00	1098.62	± 16.79	14.96	± 0.94

test, for parameter δm - displacement of the opening tip of the crack defined by the maximum load were presented in Table 5.

The best condition of fracture toughness (qualitatively) was presented by ausforging and the worse, by hot forging. However, CTOD (δm) mean results for warm and ausforging were statistically equivalent, since a statistical difference was only observed among them and hot forging results. Therefore, in terms of fracture toughness (parameter δm), warm forging and ausforging could be considered better than hot forging.

Process	Bending Stress (MPa)	Mean ± Standard Deviation (cycles number)
Hot forging	474	1.149.600 ± 948.965
Warm forging	474	96.940 ± 38.453
Ausforging	474	6.404.833 ± 328.312

Table 4
Cycles to failure in fatigue testing in rotating bending.

Process	δ_m (mm) – Mean ± Standard Deviation
Hot forging	0.0737 ± 0.0044
Warm forging	0.0549 ± 0.0067
Ausforging	0.0537 ± 0.0036

Table 5
Results of CTOD test.

Optical microscopy

The mean size of ferrite grains are presented in Table 6. Because the ferrite grains showed no statistical differences between the transverse and longitudinal directions, the statistical analysis was only performed in the transverse direction.

For Both body and arm regions, the mean size of ferrite grains after hot forging was statistically higher than the mean of both the warm and ausforging processes. The mean size of ferrite grains in the body and arm regions after hot forging was statistically higher than the mean of both the warm and ausforging processes.

Figures 3 to 5 show the microstructure after the forging processes. Figure 3 presents the product microstructure after

Process	Mean ± Standard Deviation (μm)			
	Body region		Arm region	
	Transverse	Longitudinal	Transverse	Longitudinal
Hot forging	3.73 ±0.53	3.85 ±0.35	7.79 ±0.64	6.45 ±0.28
Warm forging	2.16 ±0.31	2.56 ±0.09	6.04 ±0.66	6.37 ±0.84
Ausforging	2.23 ±0.38	2.12 ±0.15	5.70 ±0.36	6.65 ±0.72

Table 6
Ferrite grain sizes.

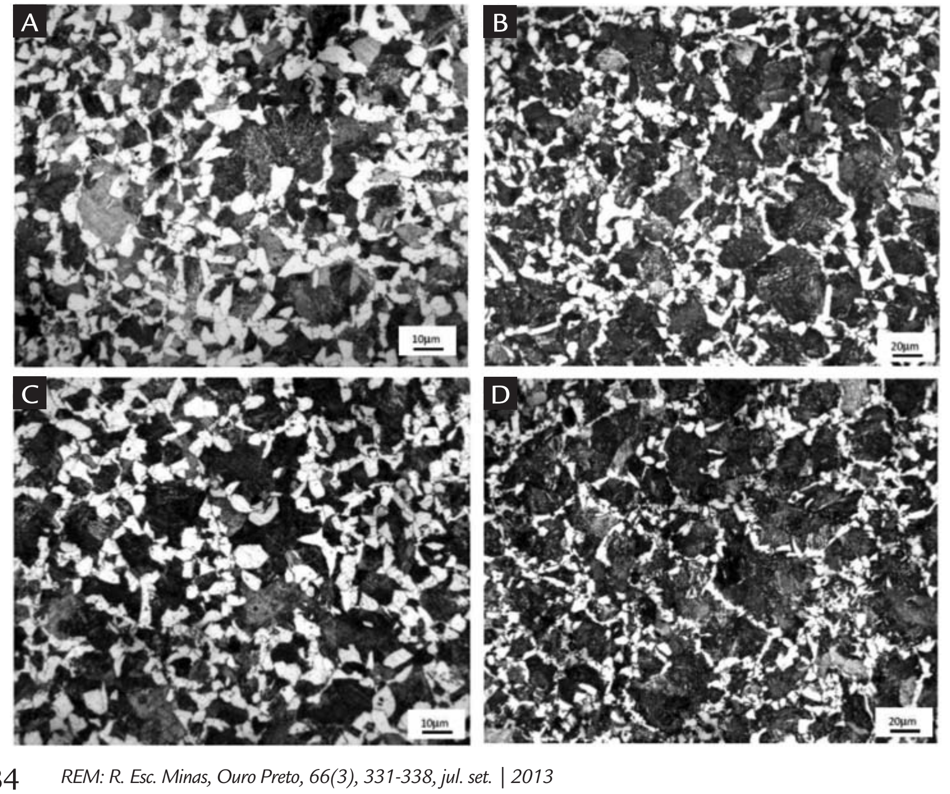

Figure 3
Microstructure of the products after hot forging formed by ferrite and pearlite grains:
A) Body/transverse.
B) Arm/transverse.
C) Body/longitudinal.
D) Arm/longitudinal.

hot forging. Microstructures shown in Figures 3A and 3C are basically ferrite and pearlite grains distributed homogeneously. However, in the microstructures of Figures 3B and 3D, it is qualitatively observed that the ferrite grain decreased and there was a higher proportion of pearlite clusters where more colonies were formed. Microstructures shown in Figure 4 refer to the warm forged products. It was observed that those microstructures present refined grains which are distributed homogeneously with ferrite and pearlite. Figure 5 illustrates the microstructures after ausforging. Figures 5A and 5C present the microstructures formed by pearlite, ferrite and acicular ferrite.

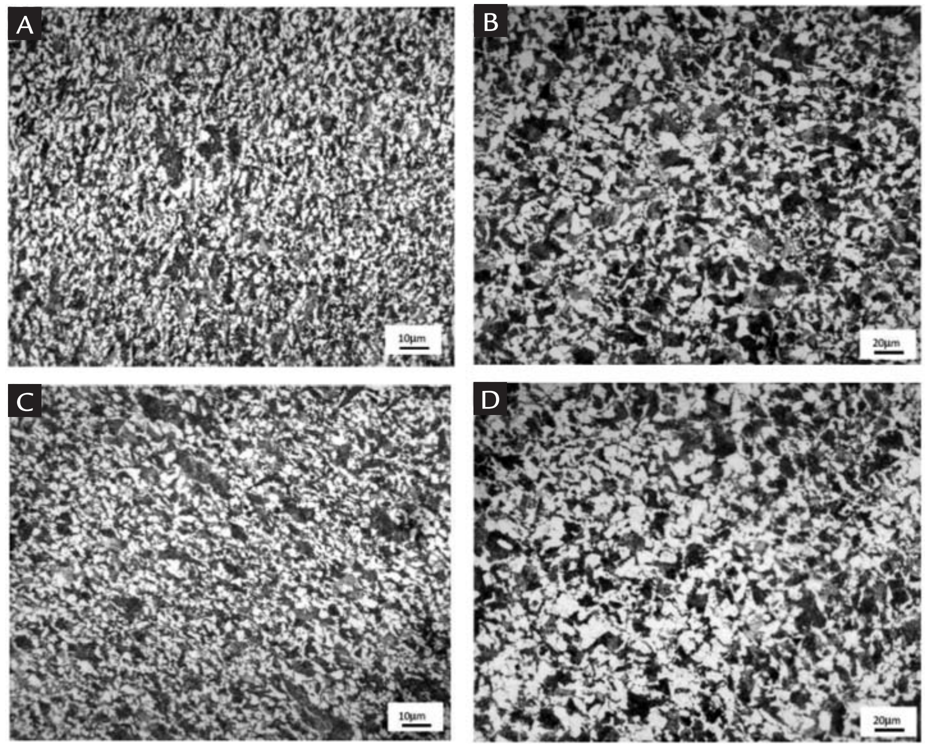

Figure 4
Microstructure of the products after warm forging formed by ferrite and pearlite grains:
A) Body/transverse.
B) Arm/transverse.
C) Body/longitudinal.
D) Arm/longitudinal.

4. Discussion

Ausforging showed the best mechanical properties (UTS and YS) with a small reduction of elongation, which is consistent with the results found by Prasad & Sarma (2005a, 2005b), Sun et al. (2012) and Dong (2012). Prasad & Sarma (2005a, 2005b) concluded that the increase of the temperature of austenitization favors the mechanical properties (UTS and YS) of microalloyed steels subjected to a thermomechanical treatment of hot rolling. They also concluded that the presence of ferrite, pearlite, acicular ferrite and granular bainite contribute to increase the mechanical strength. Previously, the same research group had found that the increase of the austenitization temperature decreases the elongation (ductility) (Prasad et al., 2003). In this work it was noticed that hot forging showed superior mechanical properties (UTS and YS) than warm forging. This result is not in agreement with other results found in literature, which refers to warm forging as a classic process to improve the mechanical strength when compared with hot forging, obtaining good combination of strength and toughness (García-Mateo et al., 2000).

The stress applied in the fatigue tests was on the threshold of the fatigue limit of the hot forged products, since there was a wide dispersion of outcomes, not resulting from the loading procedure but from the fatigue limit of the material. Statistically, the mean cycle number of ausforging was higher than that obtained in the hot and warm processes. In addition, it was found that the means of warm and hot forging processes were statistically equivalent.

Although the microstructure after warm forging was refined, it did not guarantee an improvement of the mechanical properties (Table 3). It occurred because the yield strength and ultimate tensile strength were statistically lower than those observed for hot forging. Hot forged products present a mean ferrite grain size higher in the central region, while in the region of arms, the mean ferrite grain size is statistically equal to warm forging. This result disagrees with literature, which shows that the smaller the grain size, the higher the expected ultimate tensile strength. However, the applied low soaking temperature (800°C) before warm forging favors to refine the austenitic microstructure and consequently the addition of a microalloying (Ti) is not required (García-Mateo et al., 2001). In the present study, Ti and V are microalloying agents, and therefore, the undissolved precipitates do not contribute to the final strength of warm forged products as shown in García-Mateo et al. studies (2000, 2001). On the other hand, in the conventional hot forging microalloying with elements such as Ti or V, it has become the main way to obtain ferrite-pearlite steels with a good combination of strength and toughness, as previously discussed (García-Mateo et al., 2001).

As shown in Figure 5, the microstructure is formed by pearlite, ferrite and acicular ferrite. It should be noted, considering the origin of the mentioned components, that the similarity in the appearance of acicular ferrite and bainite structures makes their identification difficult. In this study, the structure was classified by comparison with images presented in literature for wrought microalloyed steels. Some authors report that there is evidence in many cases that acicular ferrite is, in fact, bainite which was nucleated intragranularly in the material inclusions (Lee et al., 2003; Bhadeshia, 1998; Drobnjak and Koprivica, 1996, Sugden and Bhadeshia, 1989). While bainite is formed by bundles of parallel plates of ferrite, acicular ferrite is much more irregular, with plates in different plans. These bundles of non-aligned plates cause a toughness increase (without compromising the yield strength), because unlike the bainite, any formed crack should go by different crystallographic planes, hindering its spread. Prasad et al. (2003) investigated the granular bainite by transmission electron microscopy in microalloyed steels treated by thermomechanical processes and noted that it was composed of acicular ferrite and austenite/martensite.

In the arm region (Figures 5D and 5B), the microstructure also consists of ferrite and pearlite grains, but the amount of acicular ferrite apparently decreases, perhaps because the reduction of heat transfer rate and the strain increasing in this region (Silva et al., 2006). However, the ausforged products which presented acicular ferrite in the microstructure showed the highest mechanical properties (UTS and YS) among the forged products. Xue et al. (2006) and Zhao et al. (2003) also identified the presence of acicular ferrite in microalloyed steels worked by thermomechanical treatment and concluded that it contributes with the increase of the material strength.

During ausforging the deformation occurred with the austenite metastable and in the non-recrystallization region. Therefore, the fine ferrite grains might be formed by both strain-induced transformation and strain hardening, with the generation of internal defects acting as nucleation sites, since the forming temperature was below the Ac3 temperature (848ºC). It is possible that whether the strain occurred in a temperature near or above the Ac3 temperature, it would result in forging loads lower than the load obtained in this work. The main mechanism for the transformation of austenite to ferrite would be the strain-induced transformation, resulting in dynamic softening during strain, as discussed previously by Eghbali & Abdollah-Zadeh (2005, 2006, 2007).

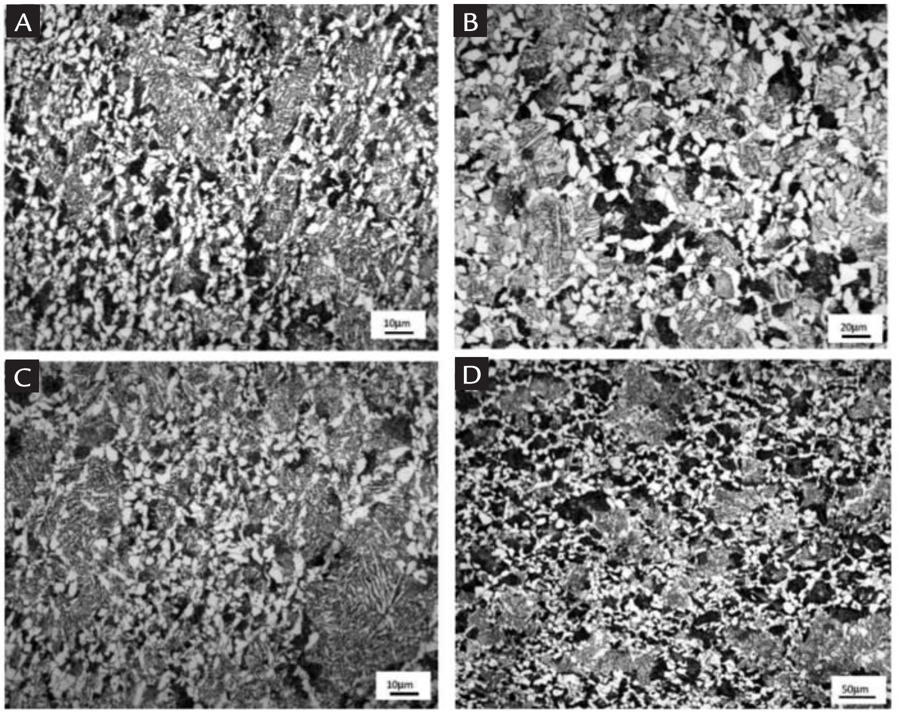

Figure 5
Microstructure of the products after ausforging formed by ferrite and pearlite grains:
A) Body/transverse.
B) Arm/transverse.
C) Body/longitudinal.
D) Arm/longitudinal.

5. Conclusion

From the results of the present study it is possible to conclude that ausforging is a viable alternative to both warm and hot forging processes, especially as regards to the overall products quality. It was evidenced by the improved final mechanical properties (UTS, YS, fatigue strength and fracture toughness), by the best forgeability demonstrated by the absence of surface defects, which was common in the other two processes, and by the forging load similar to warm forging.

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