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ORIGINAL RESEARCH

Effect of using eletromagnetic stirring on AISI 1025 steel forged flanges

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Abstract This work has the objective of evaluating the effect of electromagnetic stirring (EMS) used in continuous ingot (CI) in the mechanical and metallurgical properties of hot forged flanges of AISI 1025 steel. Three conditions of raw material were supplied and compared before the forging process: one from CI using EMS; the other, prevenient from CI without EMS, and the last, with CI without EMS, and, subsequently, submitted to hot rolling process. Billets were extracted from these raw materials to manufacture connection flanges through hot forging. To evaluate the mechanical properties of the forged pieces, tension, hardness and impact tests were done, and the microstructure was observed by optical microscopy. Macrographs and penetrating liquid non-destructive testing were also done. The results of the above-mentioned tests showed proximate mechanical and metallurgical properties approved by the reference norm (ASTM A105) of the flanges manufactured with the raw materials obtained by CI with EMS and hot rolling.

Keywords AISI 1025 steel · Electromagnetic stirring · Hot forging · Continuous ingot

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Introduction

Over the last years, researches have been intensified to improve the quality of steels came from continuous ingot (CI). The structure that is immediately formed after the solidification determines the properties of the final product, not only for casting pieces that already present, in essence, their definite shape, but that also have influence in the mechanical properties of those products that will be hot rolled to produce sheets, wires or forged pieces. In particular, the hot forging process and its stages, besides the correct evaluation of the way of deforming the ingot, can support the elimination of undesirable microstructure prevenient from CI. Hereby, processes and equipments that improved the control of chemical compounds, morphology and grains distribution, cooling speed and nonmetallic inclusions, among others, were developed to obtain better quality billets in the CI [1–5].

To reduce to the columnar zone (prejudicial to metal deformability), the segregation and the central porosity of the materials obtained by CI, the use of electromagnetic stirring (EMS) becomes a factor that differs the steel from the conventional CI. The basic principle is to generate rotational currents in the liquid front the solidification interface through magnetic fields that will move the liquid and provoke the rupture of the dendrites ends front the solidification, interrupting the columnar zone growth. In the CI, the EMS contributes to the improvement of the quality of semi finished products, because it benefits their internal structure and varies the solidification structures, influencing its on the morphology, and their mechanical properties. Moreover, it is convenient to the reduction of the amount of inclusions and gases in the product [6–10].

The dendritic structure is a common result of the casting process. The application of EMS during CI breaks the dendrites end, reducing their growth, and, consequently, when the columnar grain is formed, the rupture of this longish arm happens, forming new equiaxial crystal nuclei. The objective

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Table 1 Chemical compound of studied steels

Manufacturing route of steels	C (%)	Mn (%)	Si (%)	S (%)	P (%)	Fe (%)
CI + Hot rolled	0,25	0,61	0,19	0,01	0,02	98,94
CI with EMS	0,25	0,63	0,18	0,02	0,02	98,57
CI without EMS	0,25	0,64	0,18	0,02	0,02	98,58

of the use of EMS is to manufacture billets with the reduction of the dendritic structures. These structures are not desirable to the final product, because they reduce the mechanical properties and make them heterogeneous [11–14].

During the use of EMS, stray currents give movement to the liquid in front of the solid. This movement influences the temperature and the solute field in front of the solidifying skin, forming an equiaxial structure, since a solid–liquid pasty zone is formed between the solidified skin and the pool. A solute gradient is formed in the solid–liquid zone due to the solute partition. If the structure is columnar, the dendrites growth goes into the same direction of the solidified skin. If the solidification structure is equiaxial, the solid–liquid blending remains fluid from 20 % to 30 % of the solid. In addition, the fluid movement provokes the fragmentation of the dendrites and the multiplication of the equiaxial grains, making possible the columnar-equiaxial transition and a substantial reduction in the grain size and refinement of grains [15–20].

The control of current and frequency parameters in the electromagnetic stirrer in the mold entry will determine the quality of billets that, subsequently, will be rolled or forged. The equiaxial structure and the elimination and abrupt reduction of defects are obtained through the combination between the current (300–260 A) and the frequency (8–4 Hz) for carbon and alloy steels [21–24].

The objective of this work is to analyze the EMS effect, using parameters of 300 A and 4 Hz (supplied by the steel manufacturing company) in the mechanical and metallurgical properties of AISI 1025 hot forged flanges. The results were evaluated through: ASTM A105 norm (standard specification for carbon steel forgings to be applied in pipings), which involves mechanical properties of forged flanges; metallographic tests; and penetrating liquid non-destructive testing. These results from forgings came from EMS are compared to the steels came from rolling (traditionally supplied to the forging companies), and also, from CI without electromagnetic stirring, so that they can be suggested as an option of supplying for the forging companies.

Experimental procedure

During this work, AISI 1025 steels (with manganese and silicon additions) were used for the flange forging process. For this forging process were used steels obtained by the following manufacturing routes: CI followed by hot rolling, CI with EMS and CI without EMS. The chemical compound of the studied steels is presented in Table 1, which follows the ASTM A 105 norm; the evaluation tests of the three types of steel are presented in Fig. 1.

Before and after forging, macrographs were done using a compound reagent of 50 % of HCL (37 % concentration) and 50 % of filtered water at 80 °C, observing the ingot transversal section (120 mm × 120 mm square cross section) and longitudinal section of forgings.

For the hot forging process it was used a FNSA chamber furnace with 1500 Kg/hour capacity and natural gas heating. The pieces were heated at 1200 °C temperature during 40 min. The first forging stage was done in a MANHKE hydraulic press with 4500 kN capacity, and a side upsetting (*billet* longitudinal section). After that, an ERIE pneumatic drop hammer with 25000 kN capacity was used in the transversal section, up to the total filling of the engraving.

For the micrographic evaluation after the forging process, test specimens were taken from the flanges obtained from materials came from the three manufacturing routes. The preparation of the test specimens followed a standard procedure. At first, they were sandpapered with granulation sandpapers #120, #280, #320, #400, #600. In the polishing were used both alumina 0,3 μm and the chemical reagent Nital 2 % (2 ml HNO3 and 98 ml alcohol). The analyses of the microstructures

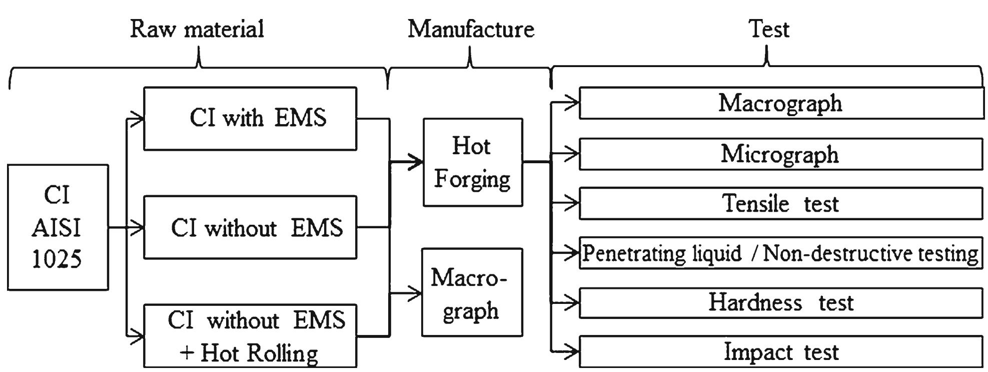

Fig. 1 Evaluation Tests

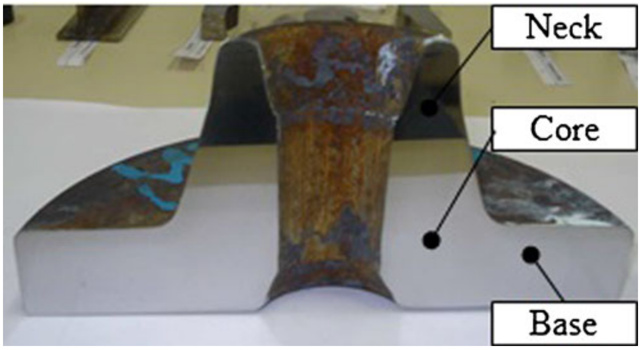

Fig. 2 Regions where the metallographic analyses and the hardness measures were done

were done in an optical microscope (Carl Zeiss Axiovert 100A model) with a coupled digital camera (JVC TK-C1380U).

The metallographic analyses and the Brinell hardness measures (187 HB maximum according to ASTM A105 norm) were done in three different regions: in the base and core of the forging, and in the neck of the flange, according to Fig. 2 below.

To detect superficial discontinuities in the forged pieces, a penetrating liquid non-destructive testing was done. To evaluate the forged pieces, procedure 2C was followed [25]. The analyses were done in longitudinal cut sections, and it was used the grinder polishing surface finishing.

The mechanical properties of the forged flanges were evaluated through tension, hardness (Brinell) and impact (Charpy) tests. The impact test was done according to ASTM E-23 norm, in room temperature. The test specimens were machined with the following dimensions: 55 mm length and 10 mm× 10 mm square cross section with 45° central miter (V-notch). The chamfer was machined in a wire electro-erosion machine. To evaluate these workpieces, three test specimens were

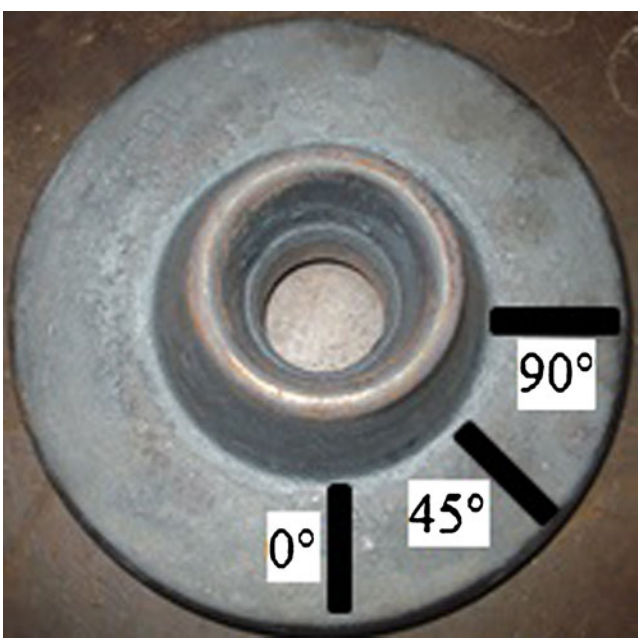

Fig. 3 Removal positions of impact workpieces

Fig. 4 Place for the removal of tension test workpieces

manufactured by initial raw material condition. Figure 3 shows the regions were the test specimens were removed from each forged piece. The test specimens were removed from positions 0°, 45° and 90°, according to the test norm.

The tension test was used to analyze if the forging follows the norm for the manufactured workpiece. Figure 4 shows, in the forged flange, the place where the workpieces for the three supplying conditions were removed and manufactured, for tension test, according to ABNT MB4 norm. The tension test results were compared to ASTM A105 forging norm, to verify if there is an approval.

Results and discussion

Macrograph analysis before forging

The macrograph analyses were done in samples of the same steel heat from conventional CI and in CI using electromagnetic stirrer. In Fig. 5, it is observed the comparison between the two

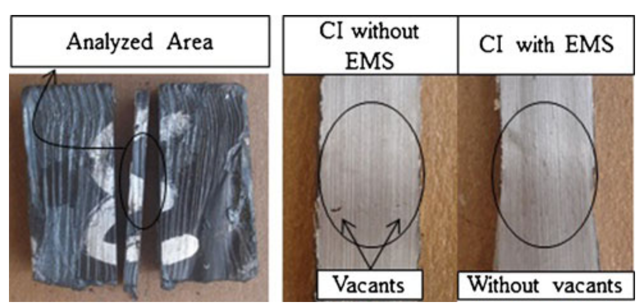

Fig. 5 Comparison of steels originated from CI with and without stirring

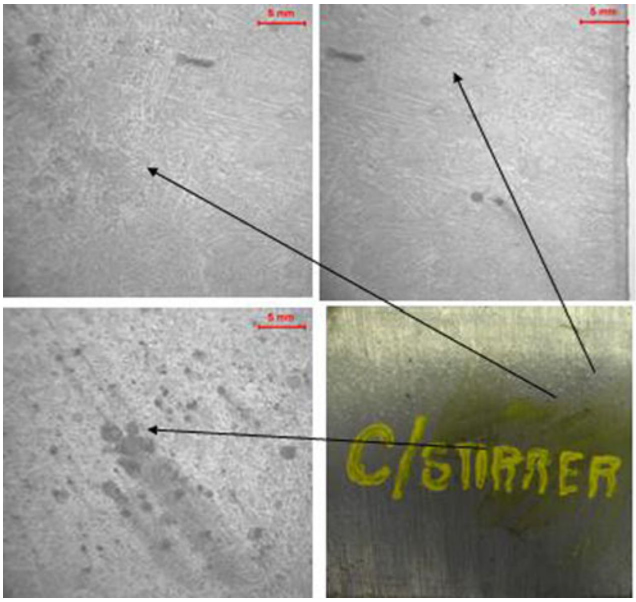

Fig. 6 AISI 1025 steel billet modified from EMS with an increasing of equiaxial grains and porosity dispersion and segregation

above-mentioned samples and the place from where the square cross section ingot material was removed (120 mm × 120 mm). Discontinuities revealed in the figures such as blanks that are concentrated, mainly, in the core of the billet – a flaw came from solidification – were observed in the analysis of the workpiece from conventional CI. EMS, instead, did not cause these discontinuities.

In Fig. 6, in the macrograph (with the attack previously mentioned) of the billet from EMS (in transverse cut) it is observed the effect of this process, from border to core, with the decreasing number of columnar grains, and in the core, with porosity dispersion and segregation. In Fig. 7, it is observed the macrostructure of steel came from conventional CI with a considerable amount of columnar grains, and central blank with apparent segregation, which is expected for this supplying condition.

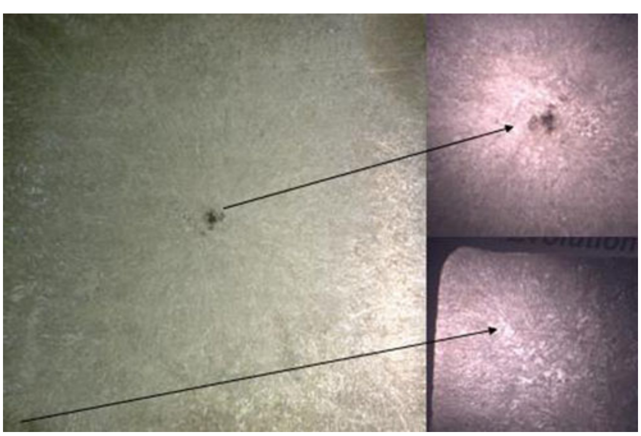

Fig. 7 Macrograph of AISI 1025 steel came from conventional CI presenting columnar grains and central segregation

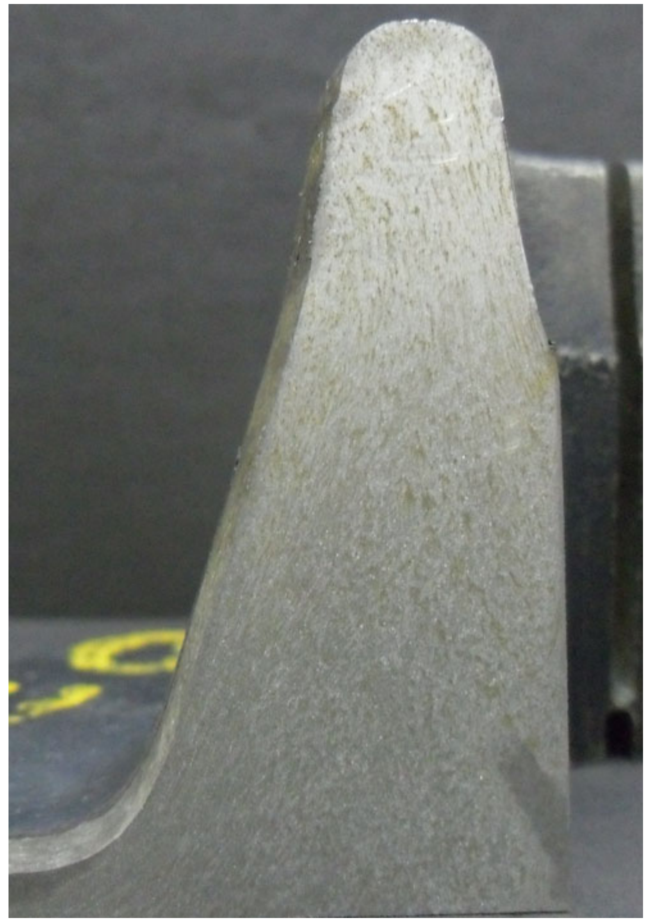

Fig. 8 Forgings came from CI with EMS with a homogeneous structure, without the visualization of dendrites

Macrograph and micrograph analyses after forging

It was analyzed the macrograph of the materials obtained by the three processing routes after the forging of the flanges. In the forged piece came from rolling, mechanical fibering lines

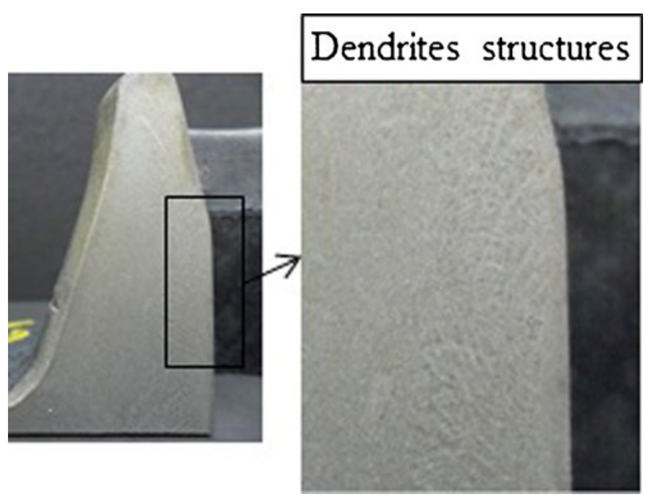

Fig. 9 Macrograph of forged steel came from conventional CI presenting a dendritic structure

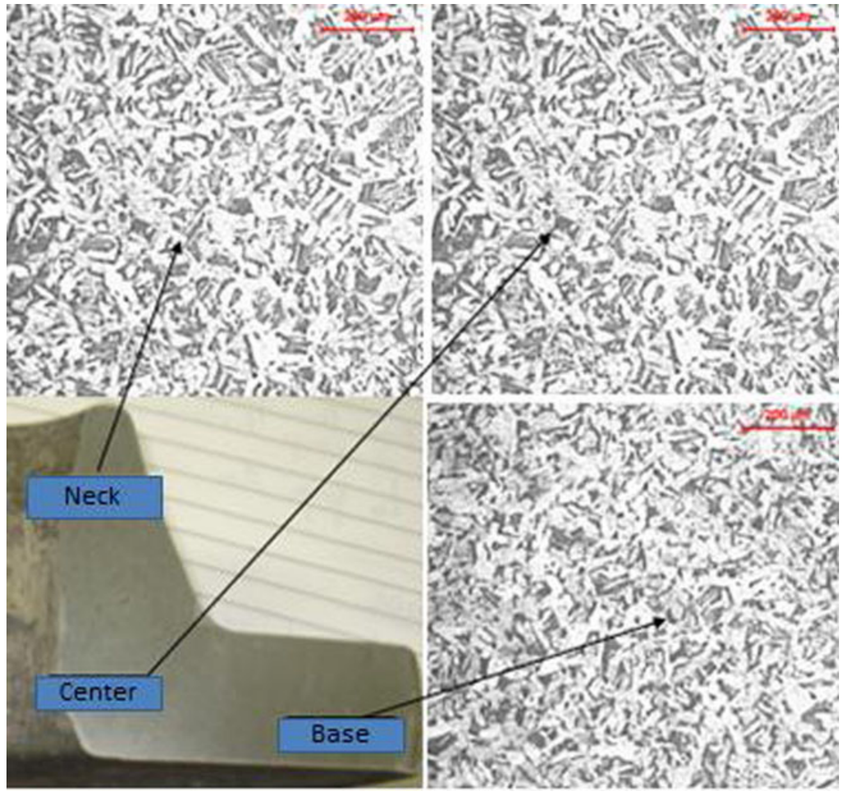

Fig. 10 Micrograph of forged steel from hot rolling

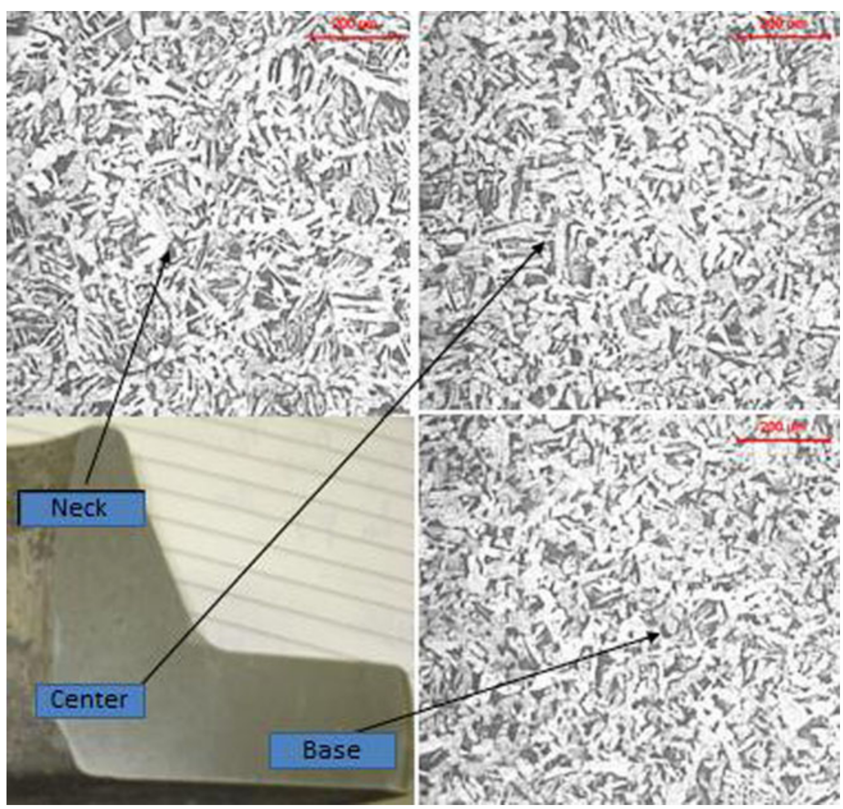

Fig. 11 Micrograph of forged steel from electromagnetic stirring

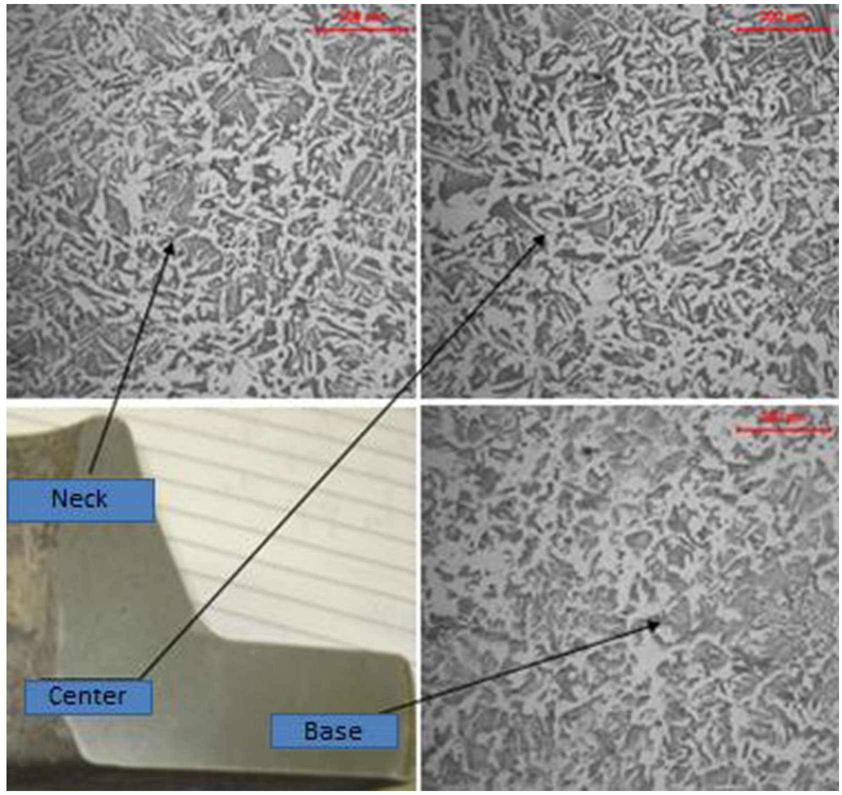

Fig. 12 Micrograph of forged steel from conventional CI

were verified as expected [26–28]. In the forged pieces from CI with EMS, a mechanical fibering is observed according to Fig. 8. This fibering was obtained during the forging in two workpieces; however, in a less clear way than the one came from rolling, due to a granulation obtained from solidification, but without the visualization of the dendritic structure with columnar grains, expected for a piece came from CI, i.e., one that shows the EMS effect.

Figure 9 shows the macrographs of the forged pieces came from CI without EMS. Regions with dendritic structures (non-eliminated in the forging process) can be observed.

For micrographic analyses slitting in flanges were done, and the microstructures obtained in the base, core and neck regions were observed for comparison between the three forged types.

At first, the micrograph of forged steel came from rolling, presented a more homogeneous structure in relation to the other two, as expected. It was verified that the microstructure was constituted almost exclusively from approximately polygonal ferrite, or allotriomorphic, obtained from re-crystallization in rolling and hot forging stages, small amount of Widmansttäten ferrite and pearlite, as shown in Fig. 10.

Figure 11 shows the results from the forged came from CI with electromagnetic stirring. It was verified that the microstructure presents a considerable amount of approximately polygonal ferrite, or allotriomorphic, due to the re-crystallization resulting from hot forging, and a bigger amount of Widmansttäten ferrite compared to the material came from rolling and pearlite.

Through the same micrographic evaluation of the forged came from CI without EMS, in Fig. 12, it is observed the re-crystallization in the analyzed points due to hot forging process, but with a considerable amount of primary and secondary Widmanstätten ferrite and a rougher granulation when compared to the two previous situations in the same region.

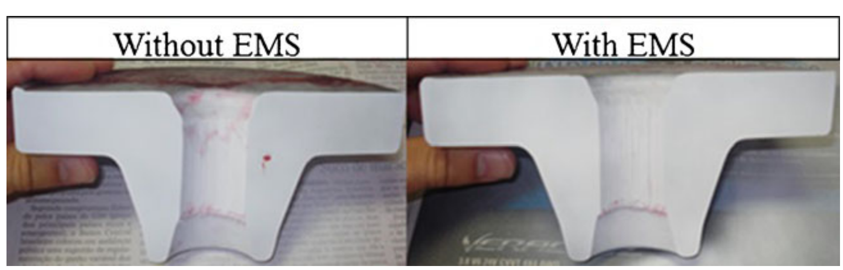

Fig. 13 In red, it is shown discontinuity in the evaluated surface of the forged from CI without electromagnetic stirring

Table 2 Impact test results

Forged from rolling	Energy absoved at impact (J)	Forged from CI with EMS	Energy absoved at impact (J)	Forged from conventional CI	Energy absoved at impact (J)
Position 0°	59	Position 0°	59	Position 0°	60
Position 45°	60	Position 45°	57	Position 45°	54
Position 90°	64	Position 90°	63	Position 90°	38

Evaluation of forgings through penetrating liquid non-destructive testing

In the analyses of after cutting, polishing and penetrating liquids application procedures in the analyzed flanges, the main objective was to find possible discontinuities as blanks and cracks in the pieces after forging.

According to the penetrating liquids process, after the application of the developer, the appearance of discontinuities is immediate (when there is any). In Fig. 13, it is observed that in the workpiece from CI without EMS (left side), despite hot forging, a discontinuity appears in the evaluated surface in the internal side of the flange between the neck and the core. However, in the forged piece from EMS, nothing had appeared (right side).

Evaluation of hardness, tension and impact test results from forged pieces

In Table 2, according to the results obtained from the three points of each workpiece, it is observed constancy in the results of the forged steel from rolling and in the steel from CI with EMS in relation to the absorption of energy in the impact test. However, the steel from CI without EMS presents results with a larger variety of energy absorbed in the test (60 J at position 0°, 54 J at position 45° and 38 J at position 90°)

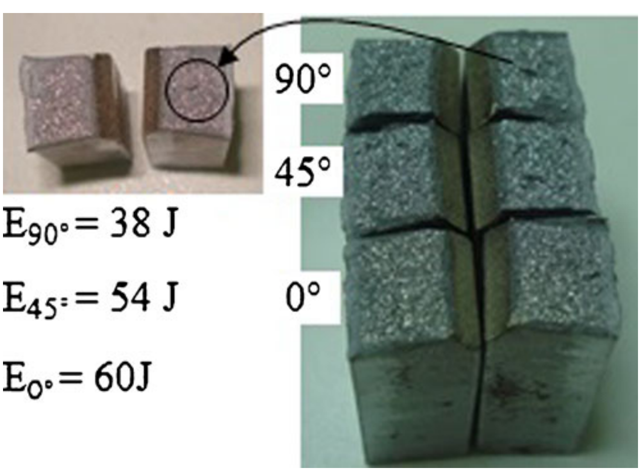

Fig. 14 Workpieces impact test of steels from CI without EMS with a highlight in discontinuities

showing a considerable variation in the absorption of energy of the workpiece.

Figure 14 shows the workpieces after the impact tests of the forged steel came from CI without EMS, highlighting the workpiece in position 90°, which presented a lower absorption value in relation to the other two, besides showing discontinuities after the fracture.

Validating the tension test in which the workpieces were removed from the most requested part of the forged flange, the forged steel from rolling had as flow and resistance limits, and elongation, respectively, 355 MPa, 490 MPa and 27 %. On the contrary, the forged steel from EMS had as after flow, resistance and elongation limits, respectively, 351 MPa, 572 MPa and 25 %. The tension test came from conventional CI without EMS. It had as flow and resistance limits, and elongation, respectively, 160 MPa, 350 MPa and 21 %. According to these results, they would be rejected by the reference norm. Through these results, there is a comparison between the types of steel, validating the steel from CI with EMS, because their results, besides being close to the forged came from rolling, they are following ASTM A 105 reference norm, used for this type of forged. This is because, according to the mechanical requisites of this norm, the minimum flow limit has to be 250 MPa, the minimum resistance limit, 485 MPa, and the minimum elongation of 22 %.

In the Brinell hardness test, after the core, base and neck measures of the three types of forged being done, the ones from rolling and the one from CI with EMS had a hardness average below 187HB (maximum accepted by ASTM A 105 norm), while the one came from conventional CI, had hardness points above accepted by this norm (average between the measured points: 192 HB).

Conclusions

These work results point at the use of steels came from CI with EMS as an option to the steel from rolling, traditionally used in the forging industry, since the mechanical and metallurgical requisites proved this supplying condition. Considering the chemical compound convenient to the forged flange (according to the reference norm ASTM A105), in the macrographs done before forging, it was proved that EMS reduced the segregation and porosity, and did not leave the central blank, that is a common situation of the conventional CI process. It also reduced the amount of columnar grains that are damaging to the deformability of the material that will be forged. The reduction of the columnar grains means more homogeneity of the product.

The EMS is a process used in the industry to the cast pieces with the function of eliminating flaws from solidification process and obtaining better metallurgical and mechanical qualities. To evaluate these forged pieces, the effectiveness of AISI 1025 steel was proved, because through the mechanical requisites of the standard specification norm for forged of this carbon steel, not only the forged pieces came from rolling but also from EMS were approved by the norm through tension, hardness and impact tests. It was also proved the effectiveness of steel through penetrating liquid non-destructive testing and metallographic tests, in opposition to the forged came from CI without the use of EMS, according to the results shown in this work.

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