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# COMPUTATIONAL SIMULATION OF SOLIDIFICATION AND HOT TEARS IN STEEL PARTS CASTING

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***Abstract.*** *This study is predominantly concerned with the cracks formed during the solidification phase (hot tears). These cracks appear both due to metallurgical and mechanical reasons. In the metallurgical viewpoint the main causes are linked to the chemical composition of the steel, to any existing impurities and to the quantity and morphology of the included inclusions. The mechanical problem is inherent of the whole casting process because of the failure of a given region to resist a certain level of stress. Moreover, the mechanical behaviour in solidifying body is more complex than in conventional mechanical problems, because the thickness of the solid shell is continually changing and the numerical models for simulation do not work in a continuous form but in a piecewise manner. Hence, this work uses numerical methods to perform simulations of metal casting, following experimental tests in steel specimens where some of the variables of the casting process were altered. This work also attempts to spread the use of computational methods by encouraging the foundryman to apply numerical tools as a mean of more suitably defining the above mentioned variables in order to minimise production losses and improve the reliability of the whole metal casting process.*

***Keywords***: *Numerical simulation; Casting defects; Hot tears in steel parts.*

## 1. INTRODUCTION

With a gross income of around 2.7 billion dollars per annum and employing some 40,000 people, the metal casting industry has grown significantly in Brazil in the last decade. Currently, according to 34$^{th}$ Annual Census of the World Casting Production published by Modern Casting (2000), the Brazilian foundries production appears in the 11$^{th}$ position.

Although 77000 tons of steel parts are produced every year, a significant amount of parts is systematically rejected due to problem in the manufacturing process, rising the costs for the manufacturers and, also, for the environment. Among the defects, a great proportion is connected to the formation of discontinuities, mainly cracks. These cracks can occur in the different phases during the metal casting process, in the thermal treatment and even in the usage of the produced part.

Casting is a process to manufacture metal parts that represents the shortest way between the raw material and the finished components in good condition for use. The casting process consists of filling up the cavity of a mould with molten metal. The mould has the exact dimension and shape of the desired part. After solidification and cooling the finished parts have the defined shape and dimensions. However, in some cases, they have to be machined the reach the necessary requirements, according to the use. Hence, casting presents the following characteristics: smooth surface finish, satisfactory dimensional accuracy in complex shapes, good production rate, good near-net shape, and low piece price. Also, if sand casting is used, the process presents almost no size, weight or shape limits. Sand casting is the process where compacted sand is placed onto wood or metal pattern halves, removed from the pattern, assembled and the molten metal is poured into resulting cavity. At the end the moulds are broken to remove the castings.

The above advantages depend upon the casting process used and are used to determine the suitable process for each particular piece to be produced in the automobile, mechanical and ore industries. Therefore, materials like metals/alloys have been processed using many kinds of casting and materials, to get the best product.

The cycle of production of a cast piece can be briefly described as below:

- Elaboration of the casting project that means the analysis of the design and definition of the process (according to the series, finishing, etc.).
- Design of the filling system.
- Manufacturing of the pattern making and core box (to get the inside shape) that can be in wood, metal or polystyrene (in case of the pattern)
- Moulding of the pieces by a suitable process as in sand, metal mould or ceramic shell.
- Melting and pouring of the metal.
- Mould opening and finishing of the castings.

Here, numerous variables are present. They ease the occurrence of defects, which, sometimes, imply in the casting reject, bring as a consequence, environmental damages and losses for the producers.

The usual defects are shrinkage, porosities, oxidation, bubbles, distension and failure in the metallographic structure and cracks.

During the elaboration of the project, unsuitable results can be obtained. Consequently, it may be necessary to make new tests until the wanted project and process are achieved. This trial-and-error development method presents the following problems:

- High cost for the tests.
- Non-optimised solutions.
- Production instability.
- Long time for development, which can delay the delivery.

These problems affect directly the consumers of casting components that, because of the growing competitiveness, are looking for suppliers with quality, low costs and reduced delivery times. The trial-and-error development generates mistruth. It is in this scenario that the simulation is indicated to help the foundries to get more reliable results. The capability to foresee the defects of filling, microstructures and mechanical properties, thermal treatment, cracks, stress concentration, as well as shrinkage and porosities, transfers confidence to the end user. The simulation of the feeding and filling systems, the development of new raw materials and of rules to standardise the feeding system, the design of filling gates to reduce inclusions are currently available and have been used by the producers.

The problem to be tacked is that the majority of the foundries do not use computational tools for the stress analysis during solidification. Nowadays in most the industries, the cracks are studied using a rather empirical way, in spite of the existing numerical simulation tools that can show the development of stresses and strains deformations in the castings during the solidification and cooling. For this reason, this is the main concerned of the ongoing research and, consequently, of this paper.

## 2. THE FORMATION OF CRACKS IN CAST STEEL

The cracks are, probably, one the most common and serious defects of castings. They can be classified in five kinds, according to the moment of they occurrence (Souza and Moita, 2001):

- Solidification cracks or hot tears - Takes place in outline of the grains and is very oxidized.
- Cooling cracks - Occurs in the grains and is normally oxidized.
- Heat treatment cracks - Usually happens because of thermal shock.
- Welding cracks - Occurs in the welding process due to the high temperature gradient.
- Utilisation cracks - Occurs during the life span of the casting, because of fatigue or impact and normally is associate to the corrosion.

This investigation centres in the solidification cracks, which are the more frequent. The definition of the International Atlas of Casting Defects (AFS,1974) for hot tears is "hot tears are discontinuities with irregular form and occurs in areas under tensile stresses; they are oxidized and have dendrite fracture". These cracks can be found in many casting alloys like the iron casting, steel and aluminium alloys, and have been extensively studied in an attempt to understand the variables and the definition of parameters to avoid this defect. From these alloys the main attention has been placed in steel, especially due to the high incidence of the defect, and this is the focus of this research. Figures (1) and (2) show a crack in steel, as well as the general appearance of the fracture.

Figure 1. Cast Steel Part with a Hot Tear

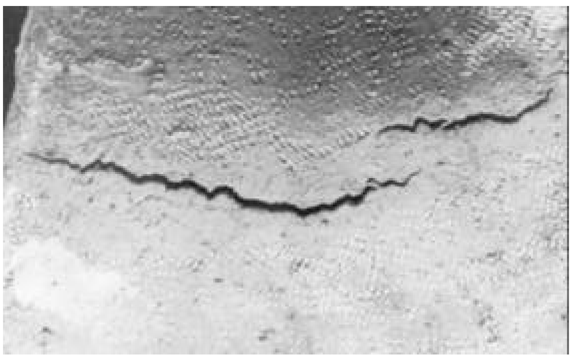

Figure 2- Fracture with Dendrite

The first scientific study of hot tears in cast steel dated of 1928 and was made by Korber and Shitzhowshi. In 1946, Briggs published a study about the mechanism of cracks formation based on the contraction properties and the steel strength.

Using simultaneous results of x-ray and thermal analysis during the formation of a hot tear, Bishop *et* al (1953) formulated a theory about the formation of these defects. This theory shows that the basic mechanism of hot cracking is the separation of a liquid film in the last stage of the solidification. The theory contradicted the earlier ones because latter dictated that the cracks were formed after complete solidification of the metal.

Later one, Middleton and Heyer & Pwowarski could prove that the formation of the crack in fact occurs before the complete solidification. In the both studies it was used an equipment based on the elastic resistance. Christopher used tests of impact (charpy) in specimens reheated in a temperature around the solidus temperature (final solidification temperature). The fracture in the test samples was fragile and metalographic test showed that there was liquid melting in the grain boundary. Christopher also concluded that the presence of the liquid metal is necessary to cause hot tears.

Some years later, Van Eeghen and De Sy tried to improve the investigation methods used by their predecessors by using continuous recording during the solidification and checking the whole process of cracks formation from the beginning. This study has proved that cracking occurs between the liquid and the solid phases as in Bechius(199-). Different authors described the crack formation mechanism for steel and cast iron (see Finardi, 1980; Guesser, 1979) and a similar behaviour to that already mentioned could be established.

In the cooling of the liquid metal there are primary dendrites in a temperature a just below the liquidus temperature (the temperature in the beginning solidification). These dendrites grow but in the beginning of the solidification there is no contact among them. At this stage the metal does not crack, even if there is tension due to the liquid contractions or the movement of the mould walls because of the low cohesion between the dendrites. When the temperature decreases, the primary dendrites grow and the alloy gets compact. However, there is still liquid among the dendrites. At this stage the risk of cracking is high once the link between the dendrites becomes weaker because of the residual liquid. Then, the conclusion is that the more critical phase for hot tearing is at the end of solidification, because the percentage of residual liquid is very low and not enough to fill the opened crack. The hot tears occur when the tensile stresses are superior of the material strength. Contraction and the mould movement influence these stresses and are influenced by several variables.

## 3. NUMERICAL SIMULATION OF CRACKS FORMATION

The numerical methods have gained increasing importance for simulation, associated to the intense development in the computational area. In solidification processes the main methods are the Finite Difference Method, the Finite Element Method and the Finite Volume Method. Because of the physical complexity, the computational modelling of casting process has provided one of the enduring challenges to the research community. For Bounds (2000) and Scwerdtfeger et al (1998), the development of stress in solidifying bodies and of the related deformations is the subject of considerable practical interest. Based on these studies, the treatment of the mechanical behaviour of growing body is more complex than the conventional problem of stress formation in a body with fixed dimensions. This difference has not been clearly recognised by most previous authors. During solidification, new layers are continuously added to the previously solidified shell. The new layer is, in the first moment, free of stresses except for the effect of the metallostatic pressure. Some seconds later, it might already be loaded by forces due to the shrinkage, caused by the cooling process.

Even when the body is completely solidified and isothermal at room temperature, it is not totally stress-free because residual stresses remain in a cast. In the stress-strain theory deformed components have associated displacements. The displacement is the distance of a specified atom from its current position to the one it had when the whole body was stress free. However, if a solidified body is not stress-free, this conventional definition of displacement cannot be applied. In this case, the definition of displacement can be given in a different way. Thus, the condition that the whole body is stress free can be eliminated and the reference state is taken to be a state in which the strains are known at the particular positions in the body.

Another factor for stress formation in solidifying bodies is the viscoplastic (creep) behaviour of the material in a region with temperature below a melting point. The viscoplastic strain rate depends on momentary stress and temperature. Hence, during cooling the viscoplastic strain varies according to the variation of temperature and stress and the total viscoplastic strain accumulated at a certain time depends upon the total stress/strain variation and temperature history after solidification. Consequently, in an exact theoretical model, the evolution of stress has to be computed continuously, starting with the time of solidification of each volume element and taking into account the continuous growth of the solid domain.

Most models described in the literature do not work in this way but in a piecewise manner, subdividing the cooling time in intervals where the strain and stress are computed. Nonetheless, this procedure allows for the simulation of casting, trying to predict and analyse the hot tears formation, as can be seen in next section.

## 4. SIMULATION OF CRACKS IN STEEL PARTS

According to Scheneider and Anderson (2000), the problem of hot tearing has been known for many years and its relationship with the alloy chemistry, the temperature and the stress has been continuously investigated. However, only in recent years, unified solidification and stress simulation has been used to predict hot tearing problems in steel casting.

The fundamental idea behind the analysis of hot tears using simulation is to couple stress/strain and heat transfer analysis at the solidifying casting. The temperature field from the solidification analysis is required as an input to the stress/strain simulation to determine the amount of thermal expansion/ contraction in the casting. The comparison of strain rate results from the stress/strain analysis with the temperature fields from the solidification analysis can be used to find regions that may be susceptible to hot tearing. When a part of the casting is simultaneously being rapidly stretched (undergoing high rates of strain) and at or near the solidus temperature, a high-risk area for hot tearing is present, as showed in hot tearing formation process. It is important when performing a hot tears analysis (as well as for a stress/strain analysis in general) to consider the effects of cores and the mould in restricting of the shrinkage of the casting during solidification and cooling. Up to now, the lack of data on the mechanical behaviour and properties of steel at temperature near the solidus temperature make the selection of a plastic strain model rather difficult.

The following example presents the hot tear analysis for a steel component. The simulations were performed in the software Magma using the modulus *Magmastress*. Figure (3) shows a steel valve body and the location of hot tears. The simulated normal strain rate along the axis of casting between 65-70% solidified is also shown.

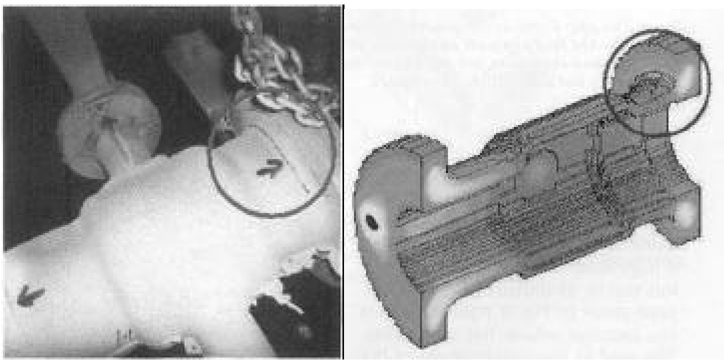

Figure 3. Cast steel part with hot tears and stress simulation (Scwerdtfeger et al, 1998)

The strain rate in the region indicated by the circle, where the hot tears develop, is much higher then for any other region of the casting and represents the area just solidified, proving the theory for cracks formation just presented.

This high strain rate can be explained in this way: this solidified metal contracts and, as it cools, pulls the two flanges towards the centre. The mould sand between the flanges resists the contraction. The result is a high rate of deformation of the casting in the region where the hot tears develops. The combination of this high strain rate with the fact that the material in this region still is hot indicate appropriate conditions for the development of a hot tears.

The evaluation of the combined results of solidification and stress/strain simulations of a casting can be time consuming. For this reason, the development of criteria that combines the results of both analyses to show areas at risk of hot tearing in a single analysis has been undertaken. The goal of these hot tears criteria is to show which areas are at risk for hot tears and the evaluation whether layout changes reduce or increase the hot tearing.

## 5. ONGOING DEVELOPMENT

The previous sections have shown the importance of the simulation for the metal casting process. As already mentioned, the main objective of this work is the use of numerical methods to perform simulations of casting, following experimental tests in steel specimens where some of the variables of the casting process were altered. Hence, the study investigates how small changes in the casting process affect the formation of solidification cracks, consequently helping the foundry operator to better comprehend the crack formation phenomenon and, therefore, to enhance the ways to prevent the problem to happen.

With this aim, in the earlier phase of the first experimental studies specimens with a big variation at the thickness between two predetermined regions, have been devised (see Fig. (4)). This is so to influence the speed of the solidification and cooling.

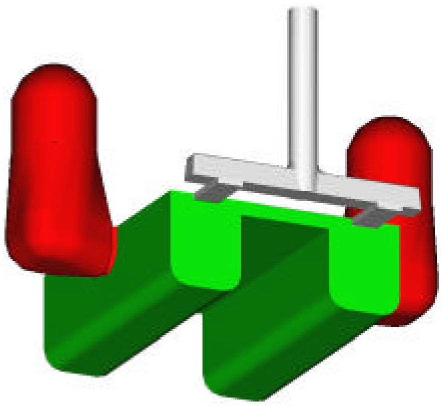

Figure 4. Specimen 1 with filling and feeding system

As can be seen in Fig. (4), at the point where the thickness suddenly changes there is a 90º angle. This is the worst situation for the formation of cracks and was designed intentionally to induce the phenomenon.

Because of the sudden variation in the thickness, the thinner part should start its contraction process earlier, while the thicker portion is still solidifying. The sand mould also contributes for the occurrence of cracks since it restricts the shrinkage of the thinner region. The test piece with a filling and feeding system can also be observed in Fig. (4).

The specimens were made using a silica resin sand mould and the material chosen was manganese steel, ASTM A 128, grade C. This material was used because of its tendency to crack. In order to minimise the metallurgical effects, a high percentage of manganese was used (low oxidation). The metal was prepared in an induction furnace and the chemical composition was checked during the process using optical spectrometry. The sand mould was made in resin-bounded sand, which can undergo high level of stresses and is commonly used in steel foundries.

The specimens were shake out after 14 hours, when a temperature was lower than 100ºC. Afterwards, they were blasted with steel shot to obtain a better surface cleaning to facilitate the inspection of the formation of hot tears. However, the visual inspection did not reveal any crack formation. See Fig. (5).

Figure 5. Final Shape of Specimen 1

The next phase was the numerical analysis of the specimen. In this case the Magmasoft Software, Version 4.1 was used. The simulation of the solidification was completed and the solidus temperature was 1330ºC. The rises and gates were not included in the stress simulation. The results of Fig. (6) show the hottest regions. These are the regions where occur the end of the solidification.

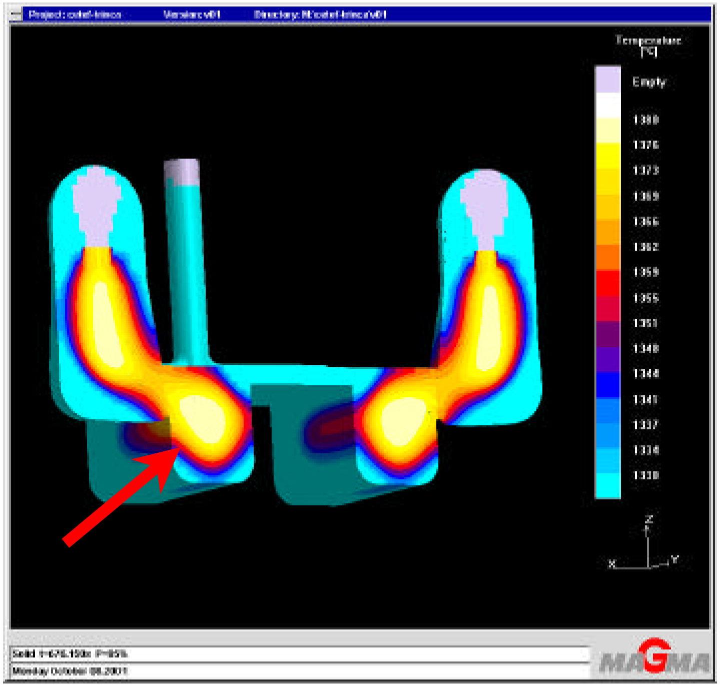


Figure 6: Results for the simulation of solidification in Specimen 1

It can be observed in Fig. (6) that the connection bar between the two parts of the specimen is away from the hottest point, indicated by the arrow. On the other hand, Fig. (7) shows that the region with strain concentration is the junction between the thin and thick sections, i.e., the link of the connection bar and the thick portion of the specimen.

As already commented in Section 2, the hot tears appear when the end solidification and the highest strain (consequently, stress concentration) regions are coincident. Therefore, the simulation gives us a good indication of why the hot tears did not occur in the practical experiments for specimen 1.

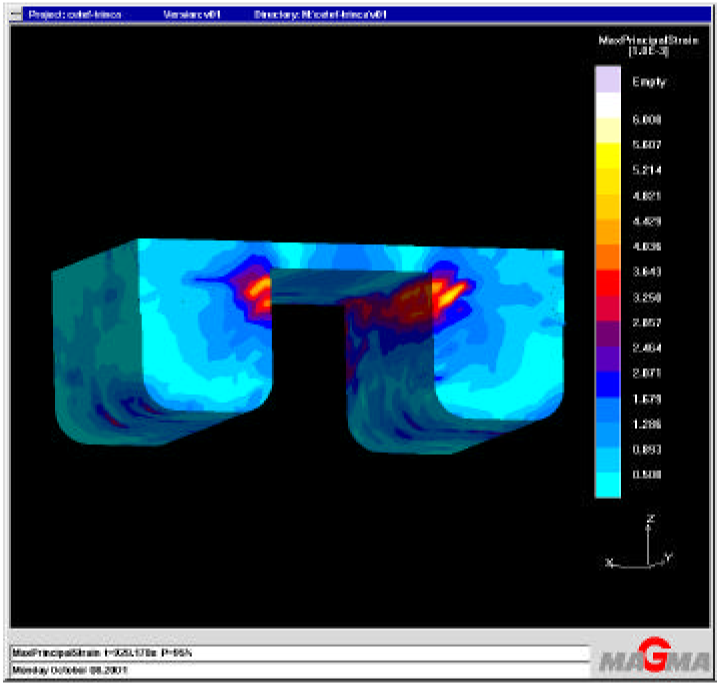


Figure 7. Strain simulation results

From the above conclusions, Specimen 2 was conceived, by modifying Specimen 1. The modification is an attempt to coincide the two regions mentioned before. The new specimen design is shown in Fig. (8) below.

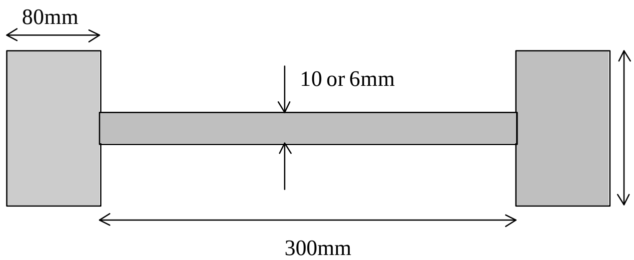


Figure 8. Geometry of Specimen 2

Note that the bar in the current specimen is longer, when compared with the first one. It also was moved to the middle of the specimen, i.e., to the hottest region. The connection bar is analysed using two different thicknesses: 10 or 6mm.

The results of the simulation with the new specimen showed that a critical situation has been reached. This means that the desired fitting between the hottest part and the highest strain can almost be achieved using this geometry. It is most evident for the case where the connection bar is 6mm thick. Figures (9) and (10) depict the results for the simulations.

In Fig. (9) the 10mm-thick bar is simulated. The results show that there is an area where the strain concentration coincides with the hottest region, inducing the appearance of hot tears. Figure (10) also shows the same behaviour for the thinner bar. However in this case the agreement is seems to be more accurate.

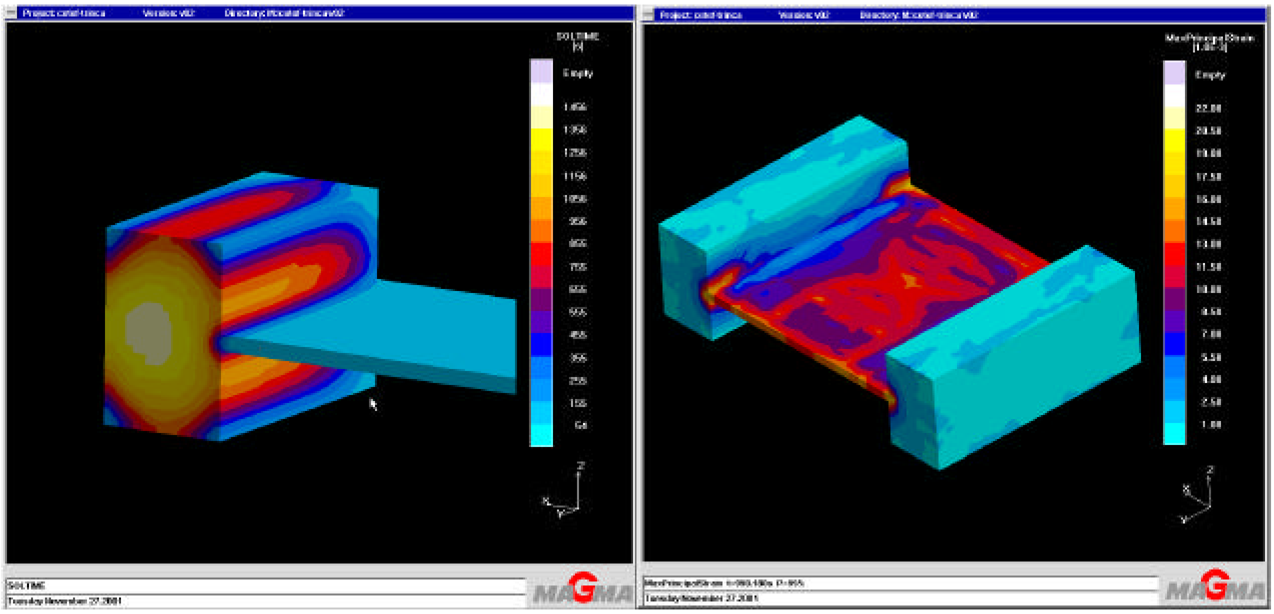

Figure 9. Simulation of the Specimen 2 with the 10mm-bar.

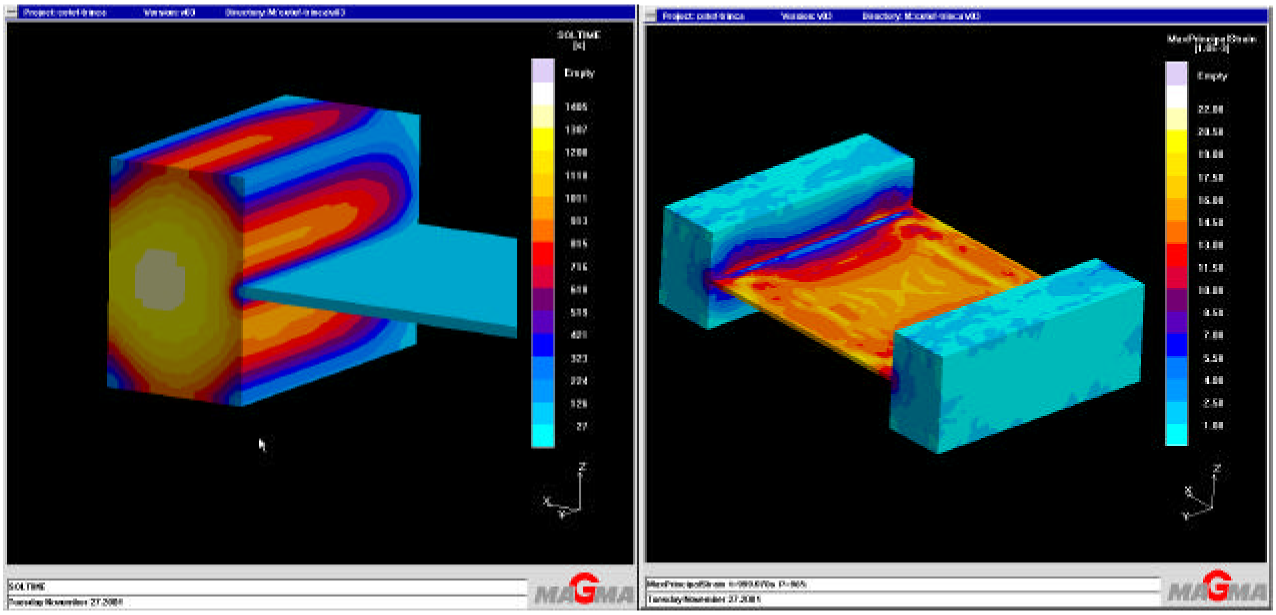

Figure 10. Simulation of the Specimen 2 with the 6mm-bar.

The next stage is to manufacture Specimen 2 and observe the crack occurrence and check the agreement with the numerical analysis. This work is currently under way and the results will be presented during the Conference.

## 6. FINAL CONSIDERATIONS

This study presents a literature review on the crack formation process of steel parts and on the numerical simulation of metal casting in order to subsidise the ongoing research where numerical results for the solidification/stress analysis combination will be validated against experimental data. It also attempts to spread the use of computational methods for the simulation of casting process by encouraging the application of numerical tools. As a consequence, the production losses should be minimised and the reliability of the whole metal casting process should be improved.

Test specimens have been manufactured in order to observe the hot tearing phenomenon. In the first set of test specimens was made and the hot tearing was not observed. This happened because the specimen geometry did not allow for the hottest portion and the strain concentration regions to coincide. A new design was sought and numerical tests demonstrate that the above agreement was obtained and new test specimens should be experimentally tested to confirm the cracking of these areas. These should be ready for presentation in the Conference.

## 7. ACKNOWLEDGEMENTS

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## 9. DIREITOS AUTORAIS