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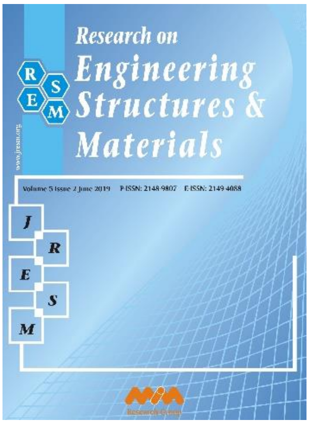

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Online Publication Date: 18 May 2019
URL: http://www.jresm.org/archive/resm2019.114ms0207.html
DOI: http://dx.doi.org/10.17515/resm2019.114ms0207

Journal Abbreviation: *Res. Eng. Struct. Mater.*

To cite this article
Funes G, Amaro P, Teixeria P, Bianchi K. Finite element evaluation of notch effect on partial penetration T-joints subjected to distinct toe-grinding processes. *Res. Eng. Struct. Mater.*, 2019; 5(4): 403-413.

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Research Article

Finite element evaluation of notch effect on partial penetration T-joints subjected to distinct toe-grinding processes

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Article Info

Article history:

Received 07 Feb 2019

Revised 15 Apr 2019

Accepted 15 May 2019

Keywords:

Welded structures;

Toe grinding;

Finite Element Analysis;

Notch effect

Abstract

Toe grinding process is widely employed for increasing fatigue life of welded structures with high dimensions, which are very usual in civil, naval and offshore industries. In these cases, costs related to the application of an additional manufacturing process are naturally justified. However, code recommendations referred to toe grinding process are quite conservatives, which justifies investigations on the applicability of more effective and efficient procedures. This work presents an alternative toe grinding procedure for application in a partial penetration T-joint with fillets subjected to a longitudinal load. Such alternative was analyzed by comparison of results of Finite Element Analysis applied over modeled specimens corresponding to three cases: i) original configuration (no grinding process had been applied), ii) tip rib contouring groove (code based procedure) and iii) straight grinding groove. This last case was proposed because the manufacturing procedure is considerably simplified and easily adaptable for automated production. After performing the FE analysis, results indicated that notch effect is very similar for both grinding cases. This result supported the choice of the simplified grinding process for manufacturing a set of real specimens, assigned for fatigue testing. In a resume, this work indicates that a simple and adaptable for automated manufacturing procedure may provide similar fatigue performance of the relatively complex method preconized by standard codes.

1. Introduction

Ribs and gussets are widely employed for improving strength and rigidity of engineering structures, especially where shell and plate components are employed. Although these reinforcements are used in a wide range of applications, from small laboratory devices to offshore platforms, in some areas they are especially important, as in the naval industry, for example. Hulls, decks and other naval structures and components are usually assembled by plate and ribs joining, which is made by welding procedures [1-2-3]. Even though this building philosophy is very successful and well consolidated, some important aspects related to fatigue phenomena are frequently neglected. A first important issue is related specifically to the welded joints, which naturally are the weakest links in the structure. High levels of residual stress and the presence of discontinuities represented by several flaws emerged during the welding process, associated with geometry and notch effect aspects, are responsible for a remarkably poor fatigue performance of welded joints [4-5-6-7-8-9]. A second issue is related to the variation of compliance caused by inserting a partial rib in a structural component, which propitiates a greater mechanical strength and rigidity in relation to the region without rib. Consequently, when load is applied, there

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DOI: http://dx.doi.org/10.17515/resm2019.114ms0207

is a stress concentration at the interface of these regions. It is worth to emphasize that such effect happens even in the case of a non-loaded rib (i.e., the force is applied in the base plate). Finally, ribs aligned with the flux of force have their beads and fillets subjected to longitudinal stress, in which case, even lower fatigue performances are expected.

Along the structural assessment phase, joint designers are frequently in face of a concerning problem: the overall aspect of the structure and the main structural components are yet established, giving no space for changing in favor of welded joints. In this case, some alternatives are available. The first one is prescribing higher levels of quality control, by non-destructive examination of critical regions of beads and fillets. Another alternative involves welding process optimization for providing a shape, in bead or fillet reinforcement, more favorable to the flux of loads, or simply for lowering the degree of inhomogeneity of the weld affected region. A third approach encompasses several post-welding processes responsible for increasing fatigue response. Thermal stress relief is preponderantly employed in small parts but, in case of the great civil, naval and offshore structures, its application is impracticable. In these cases, several post welding processes can be applied for promoting a better surface geometry, for wiping off potentially dangerous flaws at critical points on the beads or fillets and, finally, for providing stress relief or inserting localized compressive stress. Hammer peening, toe grinding and TIG dressing are the most employed procedures in case of big structures, but other processes, like shot peening and surface rolling may be circumstantially employed [4-10-11]. As a result, significant fatigue performance increases may be achieved. However, any of these processes are time and money consuming, as well as craftsmanship dependent.

Several studies evidenced that, after an ordinary but careful welding procedure is applied, in order to achieve a usual weld quality level, bead geometry aspects are of greater relevance in relation to material and metallurgical characteristics [12-13]. Fig. 1 shows the transversal cut of an idealized bead, where any material inhomogeneity is purposely omitted. In other words, this figure represents a plate of an isometric and homogeneous material with localized face protuberances that correspond to the bead reinforcements. A clear notch effect is observed, both in the face and in the root toes. Such effect is responsible for a localized level of stress usually well above the yield strength value. Fortunately, because of the high toughness characteristic of ordinary structural steels, such localized stresses are mitigated by microscale yielding. Geometrical parameters like the height of reinforcement *h* and the toe angle φ are employed for characterizing the notch effect at the face and root toes. Finally, these observations are also valid for fillet welds.

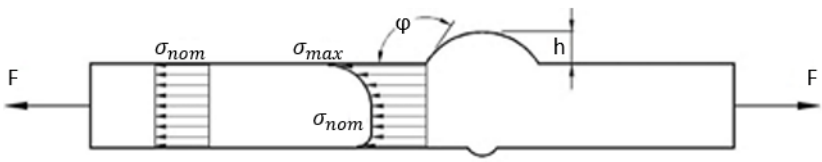


Fig. 1 Notch effect in face and root reinforcements in a butt-joint [8]

By means of the simplified image shown in Fig. 1 it is possible to comprehend some important aspects related to fatigue performance of welded joints, which in turn depends on the superposition of following pernicious facts concerned to the toe region: *i)* the previous presence of process resulted in sub-millimeter cracks, *ii)* the high level of tensile residual stress and *iii)* the notch effect yet described. A fourth issue is the high metallurgical inhomogeneity in the weld affected region, however, as already said, in conventional structural steels joined by arc welding processes, the presence of cracks, residual stress and the notch effect are more relevant.

Considering that the life achieved by a structural part in a fatigue test is dependent on the superposition of the described effects, it is possible to figure why a very low performance and a high scatter of results is always observed. Summarizing, the high level of variability in such effects is responsible for the strong likelihood characteristic of fatigue phenomena in welded joints.

In order to provide a robust assessment approach, international standards contain S-N diagrams that effectively represent the lower bound, usually corresponding to 95% of survival probability, of the whole set of structural materials and arc welding processes for the most common joint configurations. Eurocode 3 – section 1.9: Fatigue, AWS D1.1 and the IIW Recommendations [14-15-16] are examples of reference codes for welded joints assessment. Such codes are also referenced inside other standardized procedures. For example, ABS - Rules For Materials And Welding [17] adopts AWS D1.1 specifications for welded joints evaluations.

After this general explanation, it would be worth returning to the notch effect subject, but now focusing on a fillet in a cruciform or T-joint. Fig. 2 schematically shows a somewhat different but convenient definition of geometrical parameters, to be used instead of the ones presented in Fig. 1. In a fillet joint, toe angle θ (the counterpart of φ angle in Fig. 1) and the concordance radius *r* at the toe are employed.

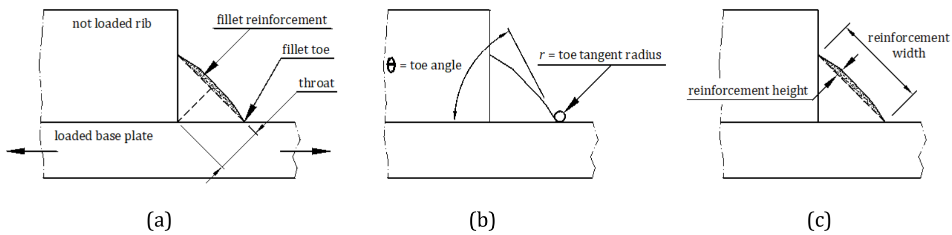


Fig. 2 Geometrical parameters for notch effect characterization in a fillet: a) fillet associated nomenclature, b) toe angle and toe radius and c) reinforcement height and width.

As already cited, toe grinding is frequently employed for fatigue life improving. The process consists of a grinding or eventually milling process applied by means of an electric or pneumatic manual device. A specifically developed tool with a blunted tip and several cutting edges, usually of high-speed steel, is adopted in the cutting process.

Fig. 3 shows a double fillet, complete penetration T-joint, after the grinding process was applied at left and right toes. At the left fillet, the final groove did not achieve the necessary depth for sub-millimeter crack removal, but groove on the right fillet was successfully applied instead. Fig. 3 also evidences that the grinding process is not able to efface cracks positioned in the weld root region.

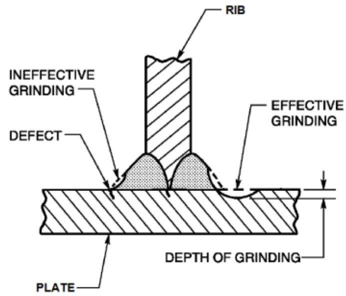


Fig. 3 Geometrical aspects related to toe grinding process [15]

Previously existent cracks at the toe are considered responsible for suppressing the nucleation period of fatigue phenomenon, which in ordinary (no-welded) parts, frequently corresponds to high percentiles (sometimes greater than 80%) of overall life. So, by effectively erasing those previously existent cracks, a nucleation period is supposedly attached to the whole fatigue life of the welded joint.

Studies evidenced that welding process associated cracks have a length inside a range flanked by an upper bound of 0.5 mm, while the lower flank is conveniently assigned to the resolution of the nondestructive inspection method employed (usually 0.1 to 0.2 mm). In order to effectively erase potentially dangerous flaws, toe grinding depth should overpass the measured crack length in at least 0.5 mm. Consequently, if any inspection procedure is going to be applied, a groove depth value of 1 mm is ordinarily specified. Such value can be a problem in case of thin plates, because of the important decrement caused in the resistance area. In such cases, an even lower fatigue response could be achieved by applying the toe grinding process. However, in case of thick plates and ribs, as the ones ordinarily employed in naval and offshore industry, the decrement in cross area is irrelevant and, oppositely, an important fatigue life increase is usually achieved [4].

Fig. 4 and Table 1 present the summary of design dimensions with respective recommended values in accordance with employed references.

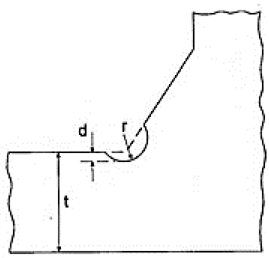


Fig. 4 Geometrical parameters related to toe grinding process [11]

Furthermore, some degree of residual stress relief is also assigned to the toe-grinding process. Such an effect is very difficult to quantify however, being completely neglected in assessment procedures.

Finally, whatever the geometry of a welded joint, loads acting on fillets and beads can be classified in longitudinal, transversal or the combination of both cases.

Table 1 Recommended geometrical parameters for the toe grinding process [11][15].

Reference	d_{min} (mm)	d_{max} (mm)	r_{min} (mm)
AWS D1.1	0.8 to 1 below plate face or 0.5 to 0.8 mm below deepest crack	greater value between 2 or 5% of plate thickness	5 mm[(2)] 6 mm[(3)]
IIW	0.5 mm below the deepest crack	7% of plate thickness[(1)]	$\geq t/4$

(1) for plate thickness ≤ 40 mm
(2) for plate thickness < 20 mm
(3) for 20 mm ≤ t ≤ 29 mm

Figure 5 shows a ribbed part with a longitudinal load applied to the base plate (note that the rib is not directly loaded). In this case, fatigue life is lower than the one expected for transversal loading, because of the uneven distribution over the throat or leg area in the longitudinal case. As the weakest link points are the extremities, any post-welding process for fatigue life improving is directed to these regions. So, Fig. 5 also shows the advised groove extension in case of toe grinding application.

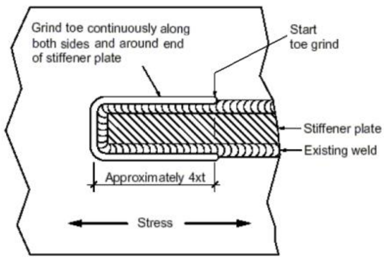


Fig. 5 Recommended contouring toe-grinding [11]

The cited reference codes seem to adopt a conservative approach in defining the geometrical parameters of the groove. However, in field or even in shop floor welding, some level of misalignment between rib and direction of the load may occur, resulting in a predominant but not exclusive longitudinal stress. Because of that, as observed in Fig. 5, the extension of the groove prolongs well beyond the critical stress region at the rib tip. Nevertheless, doubts about the ideal length to be employed naturally arise.

Finally, even though the grinding process is costly and dependent on operator hand skills, in the other sense it is clearly prone to be automated.

In face of such context, this work presents a study focused on the suitability of an alternative toe-grinding procedure, proposed for partial penetration T-welded joints subjected to longitudinal loading on the fillets. The proposed groove is applied only in the extreme point of the fillet, having a straight shape, instead of the contour shown in Fig. 5. Such proposal aims to investigate a procedure able to provide production advantages, i.e., manufacturing of a smaller and straight groove, easily adaptable for automated machining with a standard ball end milling tool, instead of a more complex but standard groove geometry. For guessing the possibility of success of such a proposal, preliminary studies on FEA software had been made in order to compare the notch effect related to original and proposed configurations.

2. Methodology

2.1. Specimen definition

The overall geometry of the T-joint specimens had been defined mostly to enable a simple machining process of the toe-grinding groove, which means that base and rib should present dimensions (and specially thickness) sufficiently high. So, base and rib were taken from a 9.53 mm (3/8 in) - AISI 316L steel plate. Other dimensions, directly correlated with plate thickness, were defined in accordance with AWS D1.1 [15] and ASTM E466 standards [18]. Rib length was defined in order to propitiate a greater length than 40 mm, as advised by NBR 8800 [19]. Fig. 6 shows the final shape and dimensions adopted in the specimen. As observed, a contour fillet with leg length of 9 mm was specified and, consequently, the joint is characterized as presenting partial penetration.

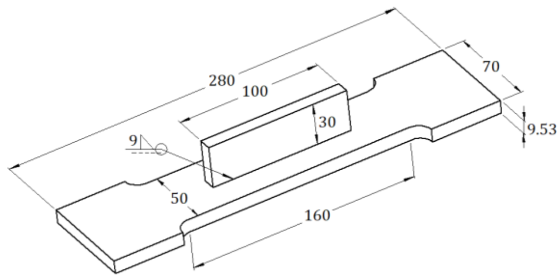


Fig. 6 Shape and principal dimensions of the specimen (mm).

2.2. Definition of Groove Geometry

Based on the specimen geometry shown in the previous section, three study cases had been defined: *i)* ordinary specimens (no grinding process was applied), *ii)* specimens that underwent a standardized grinding process (as shown in Fig. 5) and *iii)* specimens subjected to the simplified, straight grinding process. Fig. 7 shows the model elaborated in SolidWorks Education Edition software for the second case. Radius and groove depth had been defined in accordance with Tab. 1. Fig. 8 shows part of the model of the third case specimen. Radius and depth of the groove are the same as the previous case.

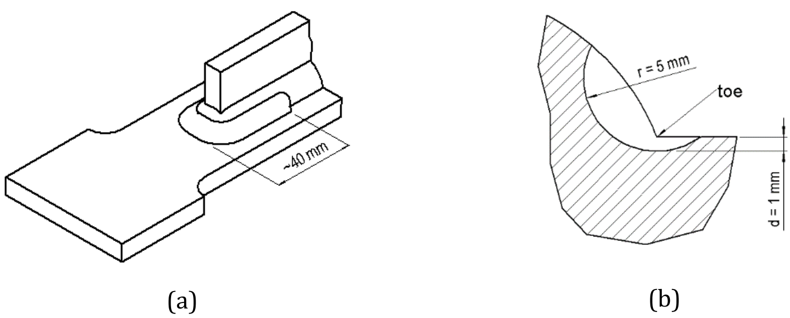


Fig. 7 Groove geometry of the second study case: a) overall geometry and b) cross cut of the groove.

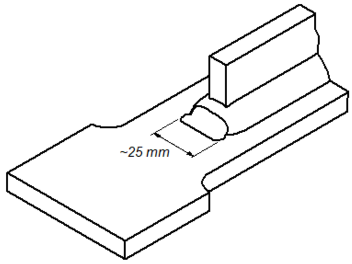


Fig. 8 Detail of the straight groove region.

2.3. Mathematical Model

2.3.1 Finite Element Meshes

A Finite Element Analysis was implemented to compare the level of stress concentration at the critical points in the contour fillet (as already explained, in the tips of the rib) considering the three cases explained in the previous section. Additional effects associated with fillet surface geometry, residual stress and any welding discontinuity probable to exist at the toe region were omitted. So, the central idea was comparing the level of notch effect mitigation propitiated by both toe-grinding procedures (standardized and alternative) in comparison with the ordinary case (without grinding).

Structural analysis was implemented in the Workbench module of software Ansys, version R15.0. The first step consisted in inserting mechanical properties of the material (in this case, Young Modulus of 193 GPa, yield strength of 207 MPa and ultimate strength of 586 MPa). Afterward, FEA meshes were automatically created by means of "Use advanced size function" command, inside "fixed" mode, allied to "sizing" method. Such set of commands enables to choose regions of interest, where a more refined mesh is necessary. In such approach, linear tetrahedral elements with four nodes were automatically generated with a user-defined main dimension.

Final mesh composition was determined by means of a convergence evaluation procedure consisting of a sequence of running and refinement steps. The resulting data was considered satisfactory when the maximum normal stress (in the X direction of the adopted coordinate system) remained in a range of variation of 5% of previous analysis value. A final main dimension of 0.8 mm for the linear tetrahedral elements of all meshes analyzed propitiated the desired result in this stage of convergence evaluation. Table 2 presents a summary of results attained in the convergence test for the original mesh (without groove). Table 3 reports the final mesh related data for all the cases of study.

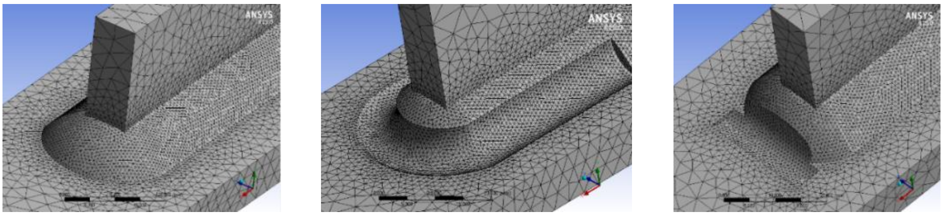
Table 2 Mesh convergence history corresponding to original case (without toe grinding).

Element size (mm)	Maximum normal stress (MPa)	N. Nodes	N. Elements	Variation (%)
3	271.8	34711	21706	-
2	308.6	62689	41300	13.5
1	363.9	202972	140221	17.9
0.9	387.8	242742	168508	6.50
0.8	390.6	298064	207662	0.75

Table 3 Mesh related data.

Geometry	N. of Nodes	N. of Elements
Without toe grinding	298064	207662
Contouring toe grinding	355210	247442
Straight toe grinding	318232	247442

Fig. 9 sequentially shows the original (no grinding) mesh, followed by the standardized and simplified meshes generated. In second and third cases, adopted values of radius and depth of the groove were the ones presented in Fig. 7.



(a) (b) (c)

Fig. 9 Resulting meshes: a) without toe grinding, b) with a contouring toe grinding and c) with straight toe grinding.

2.3.2 Boundary Constraints and Loading Definition

Before running the analysis, boundary constraints had to be specified. So the elements pertaining to one of the plate extremities were completely constrained to translation, while supports constraining one of the transversal displacements had been associated with the face plate elements. A monotonic load with a maximum value of 75 kN was applied over the face of this second longitudinally free extremity. Corresponding nominal stress value for the maximum load case is 157.4 MPa, an intermediate value to be adopted on fatigue tests phase. Fig. 10 shows a vision of the boundary step implemented inside software Ansys: A) crimped face B) with constraints on Y and Z axis and C) face where a distributed force is applied.

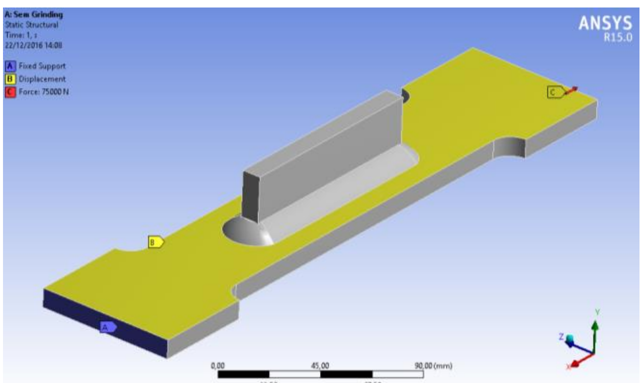


Fig. 10 Boundary conditions taking the no-grinding specimen as an example.

3. Results and Discussion

Fig. 11 shows a view of the post-processing result obtained for the no-grinding case. As observed, the toe of the rib tip fillet presents maximum normal stress, which is in accordance with experimental results reported in several welded joints assessment codes. In the performed analysis, maximum normal stress value attained is approximately 391 MPa, corresponding to a notch factor of ~2.5.

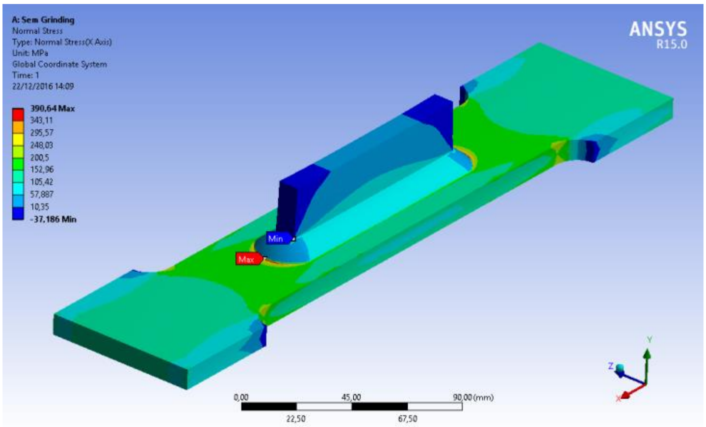


Fig. 11 Post-processing image obtained for the no-grinding case.

Fig. 12 presents a similar figure for the case of the standardized contour groove, as preconized in reference codes consulted. In this case, maximum normal stress value attained is approximately 327 MPa, corresponding to a notch factor of ~2.1. Such value represents a reduction of approximately 20% in relation to the original case.

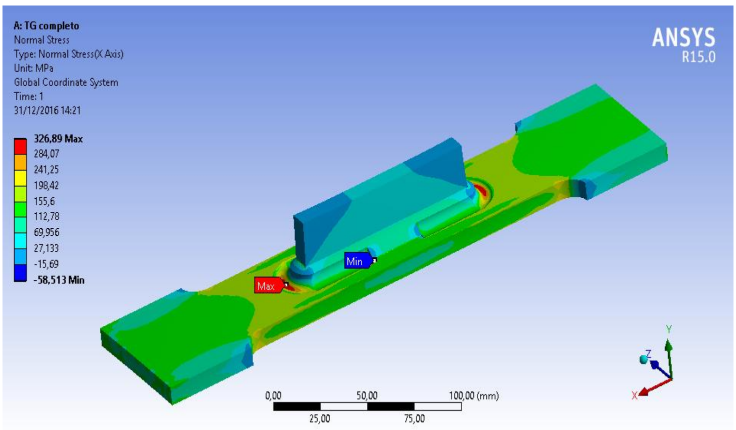


Fig. 12 Obtained results for the case of contour groove at the rib tip

Finally, Fig. 13 presents the attained results for the simplified, straight groove at the tip of rib fillet. In this case, a peak stress value of approximately 310 MPa was attained, which corresponds to a notch effect value of ~2.

These results indicate that notch effect mitigation achieved by the simplified version of toe-grinding is very similar to that attained by standardized case. The small difference between peak values of stress in both cases is inside the 5% interval of acceptance previously established.

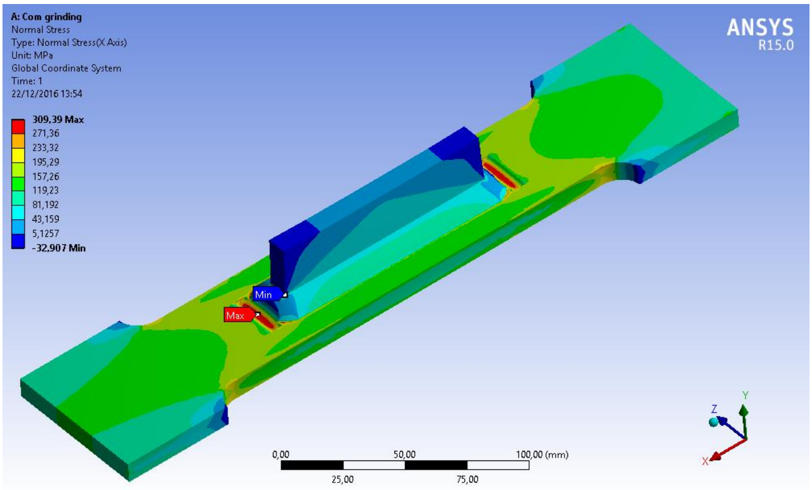


Fig. 13 Obtained results for the case of a straight groove at the rib tip.

4. Concluding and Remarks

Attained results confirm that partial penetration T-joints subjected to longitudinal loading have the toe of fillets on rib extremities as critical points of fatigue phenomena, because of the high level of localized stress. So, any post-welding procedure for increasing fatigue life shall have this region in focus.

Analyzing the reference codes and recommendations about the toe-grinding application, a clear conservative approach was observed. Such fact opened space for an alternative, more simplified procedure for grinding implementation.

By means of the analysis performed in this study, it was possible to verify that a simplified toe-grinding procedure, consisting in a straight groove, propitiates a very similar notch effect of the contouring case preconized by reference codes. In this way, a relatively simple Finite Element Analysis was very effective on describing the level of stress achieved in the structural parts, evidencing that this design tool gives support for production and manufacturing changes that may cause huge impacts on costs of naval and offshore industry.

Finally, it is worth to say that, after finishing this study, fatigue tests were made on real specimens, with stress ratio $R = \sigma_{min}/\sigma_{max} = 0$, of original (no grind) and straight groove configurations, evidencing a remarkable fatigue life increment. Actually, the attained results remained above the ones expected for the contouring groove case. Discussion of such results will be explored in a second paper.

Evaluation of a straight grinding procedure, like the one implemented in this work, shall be extended to the case of specimens with some degree of misaligned in the ribs. In such case, the apparently conservative contouring grinding procedure so far advocated by engineering codes is justified. Such future study would permit, for example, to define some level of acceptability to the misalignment of the ribs in relation to the load.

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