TECHNICAL NOTE

AN INVESTIGATION ON THE CAUSES OF A ROTOR BENDING AND ITS THERMAL STRAIGHTENING

E. Poursaeidi*

Department of Mechanical Engineering, Zanjan University
P. O. Box 313, Zanjan, Iran
Iran Power Plant Repair Company, Research and Laboratories
P. O. Box 31585/1137, Karaj, Iran
epsaeidi@yahoo.com - epsaeidi@znu.ac.ir

A. R. Razavi

Iran Power Plant Repair Company, Research and Laboratories
P. O. Box 31585/1137, Karaj, Iran
arazavi110@yahoo.com

*Corresponding Author

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Abstract Distortion or bend in a turbine rotor (especially HIP rotors) may be caused by a number of factors, either singularly or in combination. In general, the causes of rotor bend can be classified invariably in two categories: Rapidly forming permanent rotor bends and/or Slower forming rotor bends, which could trip the turbines' emergency stop. One of the major modifying solutions for rapid repairing of bent rotors is hot spotting. For this purpose, after the initial tests (visual inspection, chemical analysis, nondestructive hardness), the hot spotting was performed seven consecutive times. The results of experimental investigations and experiences with different temperatures and times showed that, the 690 ± 20˚C and 210 S. are as an optimum temperature and time respectively, for hot spotting which can provide a noticeable straightening in bent areas, in addition to having no affects on mechanical properties. Also, this results were simulated by F.E.M in view of heat distribution in different temperatures in three states (without insulation, with moisture and dry insulation), in order to find out the optimum restraint effects around hot spot area.

Keywords Thermal Straightening, Rotor Bending, Hot Spotting

چکیده یکی از مشکلات اساسی روتورهای نیروگاهی HP و IP به لحاظ شرایط سرویس دهی حاد (دما و فشار بالا) ایجاد اعوجاج یا خمش است. این مسئله که غالبا" به طور ناگهانی و بعضا" به طور تدریجی در دراز مدت رخ می دهد، منجر به خارج شدن توربین از مدار می گردد. بنابراین ارائه راه حل هائی برای مرمت روتورهای آسیب دیده از این نوع، یک ضرورت اساسی صنایع نیروگاهی است. در این مقاله، از میان روش های ارائه شده برای خمش زدائی روتور های اعوجاج یافته صرفا" روش عملیات گرم کردن موضعی (Hot Spot) مورد بررسی قرارگرفت. بدین منظور پس از انجام آزمایشهای اولیه (کوانتومتری، سختی سنجی، اعوجاج سنجی) بررسی پارامترهای اساسی در روش مزبور (دما و زمان) و سپس تعیین حالت بهینه برای هر کدام از پارامتر های منتخب با انجام عملیات گرم کاری موضعی در طی ۷ مرحله متوالی در دماها و زمان های مختلف بر یک روتور صورت گرفت. حاصل این پژوهش صنعتی دستیابی به دمای ۲۰ ± ٦۹۰ درجه سانتی گراد و زمان ۲۱۰ ثانیه برای تأمین اهداف خمش زدایی بود. همچنین افزایش توان توقیف کنندگی با عایق مرطوب از جنبه اثر نحوه توزیع حرارتی بر میزان خمش زدایی به کمک روش اجزای محدود نشان داده شد.

1. INTRODUCTION

The CrMoV-type steels with upper bainitic microstructures have been used world wide for high Pressure (HP) and intermediate-pressure (IP) steam turbine rotors. Typical inlet temperature for these HP and IP turbine element is 540˚C (1000˚F). Therefore, an HP or IP rotor operates in a temperature range where supply problems during service such as: Temper embrittlement, creep, thermal fatigue, corrosion, local distortions and so on [1]. However in this article only some problems which are related to permanent distortions (Bend) were discussed, since high temperature and pressure rotors suffer essentially aforementioned condition. In general, the causes of rotor bends can be classified invariably in two categories: Rapidly forming permanent rotor and also slow forming rotor bends. The major factors which enter into the former category mainly include: rubbing and thermal shocks. Permanent deformation of rotor due to rubbing essentially is affected by the loss of clearance between rotating and stationary turbine parts, and this is one of the most commonly encountered causes [2].

Through the years, different techniques have been developed for the straightening of bent members by the precise application of heat, hammer blows, or transverse force, singularly or in combination [3].

Heat straightening method is based on restrained thermal expansion of metal causing as upsetting action. Holt, et al has summarized the method as follows: “The method of applying heat must be such that the steel instead of expanding in length will upset, or expand inward, so to speak. Also to make this method work well, there must be portions of the member that’s, cold enough, strong enough, and situated so to force the metal, to upset or expand inward when and where it is heated, unless some outside force can be added [4].

The use of a transverse force can frequently be of value, when straightening with heat. By producing compression on the heated portion of the member, upsetting is facilitated.

Harrison and Mills, et al introduced the principle that, steel under tension tends to yield, to relieve tension, if subjected to light hammer-peening in the tension area. The principle is useful in straightening, the shorter edge of a member can be lengthened. With the transverse force acting to provide compression along the longer edge of a bent member, the shorter edge in tension, may be peened to speed the straightening [5].

1.1. Historical Research Since, the investigated rotor was repaired by hot spotting, therefore a summary review of previous heat straightening research is presented in this section. This section presents a summary of the earliest researches involving heat straightening damaged steel members. These initial studies focused on developing a better understanding of the thermal stresses, plastic deformations and practical applications of heat straightening. Fabricators have employed thermal stresses for dimensional modifications since the 1930’s .These stresses have typically been used to camber and sweep steel bridge beams, but more recently to repair damaged bridge beams. Bridge beams are usually damaged as a result of over-height trucks, fire, wind, earthquake, blast, mishandling, out-of-control vehicles, and over-loading. Early heat straightening repairs were performed with insufficient scientific rationale. Hence, early research studies were focused on understanding the thermal expansion and contraction properties of the steel and general procedures for applications.

In 1938, J. Holt, et al wrote one of the first technical papers on heat straightening. Holt, et al addressed the power of thermal contraction and its effectiveness in dimensional modification of structural steel members and procedures for heat straightening steel members damaged to various configurations. This paper was revised and published in 1955. Additionally, Holt, et al published three papers on the subject of heat straightening that provided practitioners with heat straightening guidelines. In his first paper, Holt addresses procedures for applying a Vee heat pattern and the importance of not retracing the serpentine path of the Vee heat pattern as the pre-heated material provides the necessary confinement. Holt also addresses how steel can be monitored by visual inspection. At about 1200 F, steel appears as dull red color. The steel color appears satin silver with a shade of four welding lens [6].

Three comprehensive studies have been conducted to summarize prior experimental data and knowledge and also to provide guidelines for practitioners.

The first paper, addresses the effects of external restraints as well as the application of different heating patterns such as the line heat, spot heat, strip heat, and the Vee heat.

The two later studies have provided substantial scientific data by experimental and analytical studies to support recommendations for damage assessment, optimization of heat straightening techniques, and development of heat straightening repair procedures [6].

In general, prior to heat straightening research the following objectives have been addressed:

- Heating temperature
- Heating time
- Geometric size
- Geometric of heating pattern
- Initial yield strength
- External and internal restraining forced and
- Quenching media [7].

2. A CASE HISTORY ON INVESTIGATED BENT ROTOR

In September 2000 a straightening project was performed on a 200 MW steam turbine. A typical view of this bent rotor has been shown in Figure 1. The aforementioned rotor has been in service for about 90000 hr, after which the Russian manufacturer overhauled it. After the last overhaul the rotor was put back into service but when it reached about 500 RPM, the sealing which was near the coupling was touched. Subsequently a run-out check had been performed and showed that the rotor suffered a kind of distortion. To correct the axial run-out on the coupling end, some shimming plates were added between the HP-and LP rotor coupling. Then the rotor was put back into service again. This time the rotor was run up to about 1200 R.P.M after which, it stated to vibrate heavily.

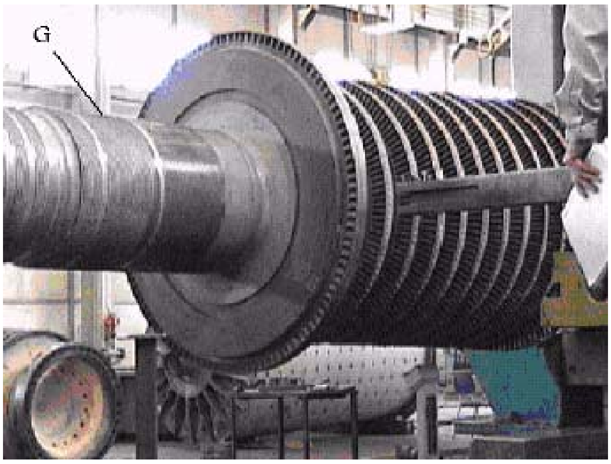


Figure 1. The bent rotor in shaft area (denoted by G).

3. EVALUATION OF AS RECEIVED ROTOR

This evaluation was done in two aspects: initial evaluation was performed in terms of damage extent, in bent rotor especially in the shaft section where maximum damage had occurred. Second, evaluation was done in order to identify the variation of metallurgical properties i.e. Chemical analysis (Table 1) micro structural character (Figure 2). In order to investigate micro structural variations on bent area of rotor, it was decided to use the surface replication technique, hardness measurement (Table 2). The results of the above tests were suitable adaptation to standard values.

3.1. Visual Inspection Although, the general impression of the rotor was validated to have rather a good condition, however, it was found that the rotor suffered some rubbing marks as described below:

- ❖ Most of the seals in the HP sealing area, locally up to about 1mm depth
- ❖ Some of the tip shrouds of several blade stages locally up to about 0.5mm depth
- ❖ Some of the seals in between the blade stages up to about 1mm depth

3.2. Initial Run-Out Test In order to determine the extent of distortion i.e. bending, an initial run-out test was performed on 15 points of the rotor. Results of initial run-out indicated that the rotor had a maximum run-out about 0.45 mm at the position denoted by G (refer to Figure 1). It was also observed that, the position of high bending was exactly 180° away from rubbing marks on the rotor. As a final result from initial evaluation, it can be claimed that, the major causing of bending in the considered rotor, has been the rubbing, owing to the loss of clearance between rotating shaft and stationary parts. Of course, there are many reasons for the loss of clearance between rotating and stationary parts in the turbine. Three of the major reasons are listed below in the frequency of importance:

TABLE 1. Chemical Analysis of Bent Rotor.

% C	% Cr	% Mo	% Mm	% Si	% V	% P	% S	% Ni
0.2	1.3	1.1	0.5	0.3	0.25	0.035	0.035	0.3

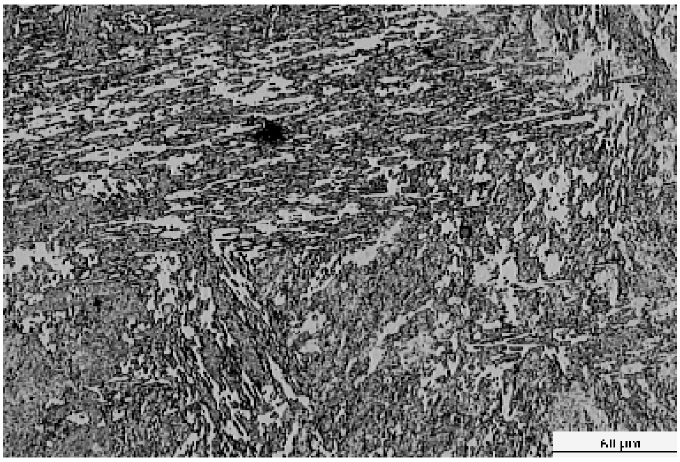


Figure 2. The bainitic structure of bent rotor (taken by replica).

TABLE 2. General Mechanical Properties of Bent Rotor.

R_e ($\geq N/mm^2$)	R_m (N/mm^2)	HB 30
540	690-850	205-250

- ❖ Improper assembly of stationary parts (large and small gland seal interchangeably) around the rotating shaft.
- ❖ Thermal gradient
- ❖ The existing of a slightly eccentric center of gravity even after careful trim balancing.

In the following section, our aim investigates the mechanism of the above factors in bending occurrence of the considered rotor.

As the preceding section described, the loss of clearance due to improper assembly associated with incorrect relative movement between rotor and casing lead to excessive friction at the high spot of sliding surfaces exactly 180˚ away from G (the same maximum point of bending). The friction caused local heating in denoted area and the following occurred, localized thermal expansion and the resulting rotor bend had increased the pressure intensity and the extent of it ran in a progressive manner.

As a secondary factor, before rubbing occurrence, the nonhomogenity of steam flow through the turbine. Therefore a gradual build up of heat on one side of the rotor continued to bow it further and further (thermal gradients). Additionally, the existence of inherent unbalance has induced the rubbing occurrence. Notably, the local thermal expansion is restricted by the cooler bulk of the rotor and an axially compressive stress is thereby set up in the rubbed area. At the same time the local friction induced, so temperature increased and it caused the local yield stress to decrease. Finally compressive yielding eventually toke place, which is more likely the cause of permanent bending.

4. THERMAL STRAIGHTENING BY HOT SPOTTING

The aim of straightening is to re-establish the balance of the stresses in the rotor, by exposing it purposefully to tensile and compressive stresses [8]. Therefore, hot spotting method is one of the most complex but successful of the available straightening methods. The practitioners of this method have traditionally been very secretive about their black art, so it is worth while explaining the underlying mechanisms and the possible variations in some details [9].

Thermal straightening basically involves rapidly heating the extrados of the bend with a suitable torch, the production of local plastic deformations (compressive stresses), Then cooling down the material and thus producing tensile stresses which contribute to the internal compensation of stresses [10]. In order to achieve an effective straightening, the related practitioner must pay close attention to the following parameters such as: local metal temperature, hot spotting time, the position of maximum distortion, cooling media and the correct control of restraint.

In order to achieve a straightening effect, the local metal must exceed 650˚C (dull red) and will usually require a temperature of 700-750˚C (cherry red) for investigated rotor. Metal temperatures are checked using a thermo graphic camera in the best condition. Noting, the hot spotting temperature must not exceed of 750˚C because upon occurrence the local transformation to austenite will take place and also upon heat removal the quenching action of the surrounding cool material, locally transforms this zone to martensite. This structure is very brittle and its formation may crack, either during transformation or subsequent service [11].

This thermal process was performed seven times which is showed in Figure 3 (each time at the same maximum point of bending). To carry out the hot spotting, the rotor was put in the lathe with the maximum location of bending point. A dial indicator was positioned exactly 180˚ away from the hot spot area (i.e. underneath the rotor). During the hot spotting of the rotor, the deflection behavior versus time was recorded. Detail information about each 7 steps of hot spot is showed in Table 3.

In this article, in addition to paying attention to all aforementioned parameters, the influencing of restraint severity were simulated by F.E.M in view of heat distribution in three states in order to find-out the noticeable restraint effects around hot spot area. In order to investigate the severity of restraint effects on straightening value of bent rotor, cooling condition performed in three states were as follow:

- Heating of hot spot area without any insulation (self-metal)
- Heating of hot spot area with dry insulation
- Heating of hot spot area with moisture insulation

Then, the above condition was simulated by ANSYS software.

The selected boundary condition in this state is including:

❖ Material properties

$$C = 400\ {}^{J}\!/_{kgk}$$

$$\gamma = 7800\ {}^{kg}\!/_{m^3}$$

$$E = 207\times10^{9}\ pa$$

$$U = 0.3K = 20\ {}^{w}\!/_{mk}$$

❖ Heat flux value = $325/5\times10^{3}\ {}^{w}\!/_{m^2}$ at maximum point of bending with 100 × 50 (mm)^2 dimension.

❖ Ambient temperature was considered 20˚C.

Figure 3. The mechanism of hot spotting heat treatment.

TABLE 3. Selected Parameters in Hot Spotting for Determination of Optimum Straightening.

T(C)	t (S.)	Run-Out (mm)	Restraint Media
75-100	130	0.45	Self-Metal
180-210	260	0.45	Self-Metal
380-400	390	0.45	Self-Metal
580-600	520	0.45	Self-Metal
650-670	650	0.4	Self-Metal
650-670	360	0.32	Dry Insulation
690-710	210	0.1	Moist Insulation

5. DISCUSSION ON RESULTS

The results of thermal straightening investigations in aforementioned steps showed that the local metal temperature were selected lower than 600˚C (in the lack of any insulation), According to Table 3, the behavior of bent rotor came back to initial deflection. Another word, the nature of resulted thermal stresses was essentially elastic i.e. smaller than compressive yield stress. However by increasing the hot spotting temperature (in the same state) up to 650˚C it was implied to threshold plastic deformation due to thermal stress increment and consequently compressive yielding. Hence, the final run-out or deflection (by choosing 650˚C) was partially decreased. Since the restraint severity influences the quantity of straightening, therefore it was decided to perform the following steps i.e. hot spotting by covering the surrounded area of maximum bent, by dry and then moisture insulation.

According to the presented data in Table 3, the application of moisture insulation in selected metal temperature 690 ± 20˚C and time (210 S.) has the most influence on straightening the bent rotor. By this sequence, the effects of restraint severity were simulated by F.E.M in view of heat distribution and upsetting result.

It should be noted that, although based on related C.C.T (continuous-cooling-transformation) diagram, the inherent critical temperature (Ac_1) is approximately 750˚C, but conservative measurements imposed to the selection of the hot spot temperature must not exceed 710˚C, because of the occurrence of partially austenization and subsequent martensitic transformation [12].

As in the preceding Section 4 described, the aim of straightening is to re-establish the balance of the stresses in the rotor by exposing it purposefully to tensile and compressive stresses. For this reason, the deflection behavior due to aforementioned stresses was controlled by a dial indicator. So, based on the variations of rotor deflection during Hot Spotting process, which can be showed in a diagram versus deflection-time schematically (Figure 4).

According to this diagram, we can classify all above variation in five zones:

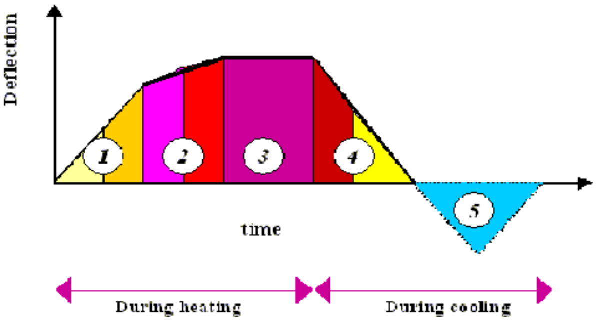


Figure 4. Ideal variations of bent rotor during hot spotting.

Zone 1 This occurred in the initial times of hot spotting process. The variations of rotor deflection in this scope are nearly linear. It is clear that the nature of deformation in this zone is essentially elastic because the resulted thermal stress is smaller than compressive yield stress. Therefore the hot spot area must bear all internal stress due to expansion. For this reason this zone is called expansion in itself or bowing zone.

Zone 2 As revealed in Figure 4 the gradient of rotor deflection gradually decreases. This is implied to threshold plastic deformation due to thermal stress increasing in hotspot area. Since the temperature of aforementioned area along with compressive thermal stress value has been increased, therefore the hot spotting zone will yield by compressive stresses. For this reason, this zone has been identified by “compressive yielding”.

Zone 3 One of the most important factors, which affect the straightening quantity, lies in the above zone. In fact by increasing temperature and thermal stresses locally, the hot spot area will undergo a noticeable plastic deformation since this area is exposed to compressive stresses; therefore it makes permanent thickening or shortening. This is why it is characterized by upsetting phenomena. This zone is the main objective to obtain straightening of bent rotor. It should be noted that, the aforementioned phenomena is seriously depending upon the rigidity or restraint of the materials in the vicinity of hot spotting area. It is obvious that the more rigidity (restraint value) of the neighboring zone, the more upsetting and the following shortening severity, therefore the straightening process will be more successful. In order to obtain the optimum upset, we performed hot spotting treatment in three states: without insulation (Figure 5) with dry insulation (Figure 6) and with moisture insulation (Figure 7) and then we simulated the above conditions in view of heat distribution by F.E.M (Figures 8-10). Another word, the straightening value of bent rotor in recent condition was more effective.

Zone 4 During this zone, the variations of rotor deformation is inverse contrary to recent stages, Because of inverse interaction of compressive stress applied to hot spot with tensile stress resulted in the vicinity of hot spot. On the other hand it should be noted that, the occurrence of martensite phase transformation which hardens and very brittle is possible, provided that severe cooling media is applied.

Zone 5 This area represents the over-straightening zone. It is obvious that the more over-straightening the rotor, the more successful the actual straightening process would be.

6. CONCLUSION

- The optimum temperature required for straightening objectives of high pressure rotors [CrMoV low alloy steel] is 690 ± 20˚C. The aforementioned temperature is conservative, to prevent the occurrence of martensite transformation.
- The optimum time required for straightening the investigated rotor is 210 S. The selective time provide a suitable thermal gradient and consequently sufficient thermal stress.
- The results of experimental investigation by F.E.M indicated that, the maximum restraint effects are obtained by using moisture insulation around the hotspot for more upsetting (0.75 mm). Case study of this analysis showed that, the upsetting value in dry insulation is equal to 0.69 mm and in the state of without insulation is equal to 0.56 mm. So, according to above results, it is proposed to perform hot spotting by moisture insulation around the hot spot area to obtain optimum restraint effects.

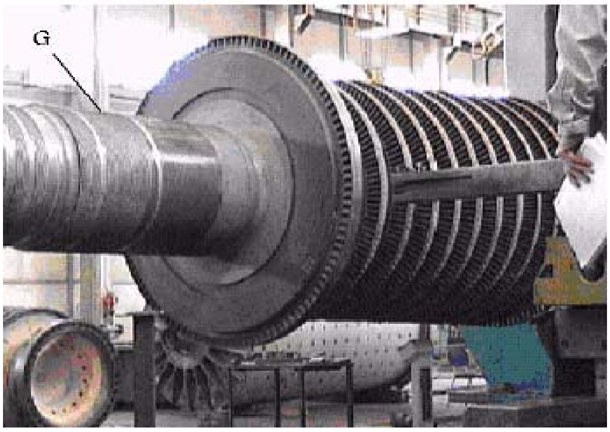
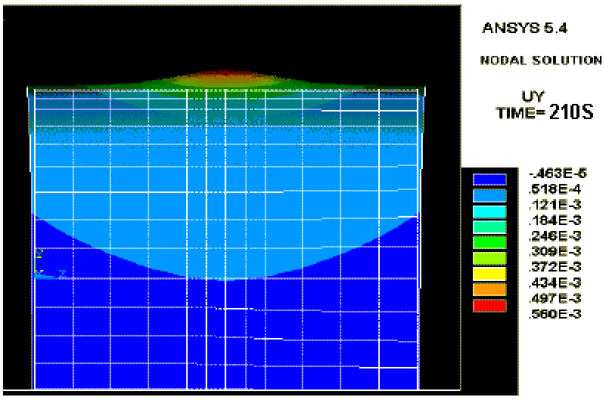


Figure 5. Utilization of locally hot spotting on bent rotor without any insulation.

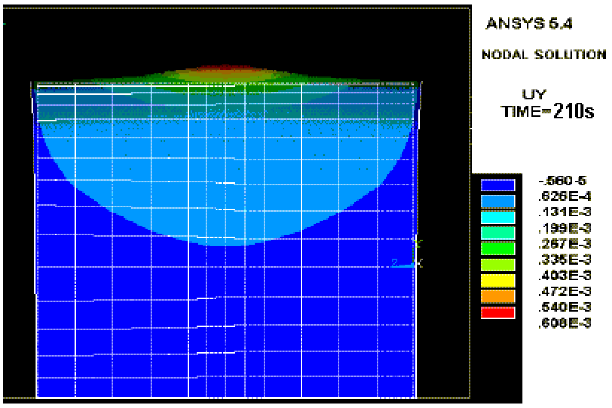
Figure 6. Utilization of locally hot spotting on bent rotor with dry insulation.

Figure 7. Utilization of locally hot spotting on bent rotor with moisture insulation.



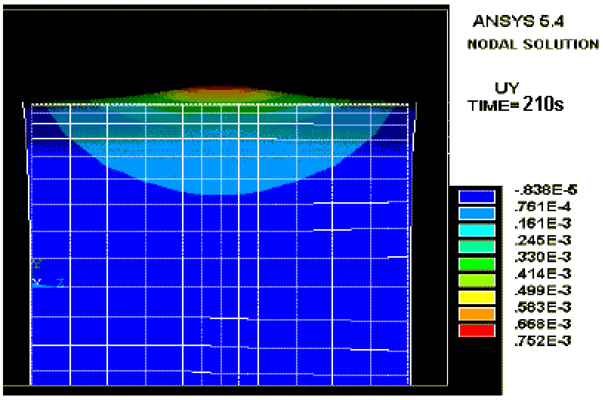
Upsetting Without Isolation

Figure 8. The occurred upsetting values in the lack of any insulation.



Upsetting Wit Dry Isolation

Figure 9. The occurred upsetting values in the lack of any insulation.



Upsetting Wit Wet Isolation

Figure 10. The occurred upsetting values in the lack of any insulation.

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