# Induction heat straightening – A distortion rework reduction tool for thin plate

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**Distortion effects encountered in the use of thin plate within the shipbuilding sector have been widely recognised as being a feature that will never be completely eliminated. Once the root causes have been identified and counteracted, the most economically and controllable form of heat straightening has to be established. In the past there has been a significant lack of knowledge or control over heat straightening processes for thin plate, and in some instances this has led to more extreme distortion in the form of thin plate buckling. The application of the Terac induction heating system has been evaluated and its benefits in reducing the rework times have been established. In addition, work was carried out to evaluate the effects that the heating has had on the material properties and the microstructure of the plate. In each case, no detrimental effects were established.**

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*Communication from BAE Systems, Surface Fleet Solutions, Glasgow/UK, and EFD Induction a.s., Skien/Norway.*

## 1 Introduction

Thin plate distortion in the shipbuilding sector has been studied for decades, but the problem continues in some form or another [1]. In addition to this, there has been a gradual move to include more thin plate into the structure of naval vessels in particular. This is normally in the form of higher strength steels such as Lloyds DH36 (or S355 equivalents). A recent publication [2] has shown that thin plate distortion can be brought down to what could be considered manageable levels. However, the work required to further reduce the level of distortion will be achieved through incrementally small gains which currently could be very costly. To generate the step change at this low level, an alternative is to develop a more efficient and controllable process of heat straightening.

Traditional processes of heat straightening have generally been developed on thicker (> 8 mm) plate. The straightening effect is generated by having one surface hotter and the other significantly colder, and thus developing the correct tensile conditions to pull the plate straight. However, when treating thin plate, it is very easy to heat through the thickness of the plate. This has the effect of inducing buckling distortion, and in a number of cases the stiffener bars associated with the area being heated have also distorted. Part of the problem in this case is the time taken to get the material up to a suitable temperature using conventional heating gases. A large amount of heat is dissipated into the surrounding region, and as a result the effects are compounded. Work carried out in Australia on 4 mm thick X80 steel has shown that the yield strength of the heated areas increases by about 6% compared to the parent plate. The X80 used in this particular situation was a low carbon Nb-Ti-Mo steel. Huang et al. [3] have very clearly summarised a number of the deficiencies of heat straightening, such as the non value added aspect, skill requirements, the possible use of water and the attendant clean up, and the high potential to buckle thin plate structures. There is also the issue about how the mechanical properties of the treated area of the plate have been affected, particularly when water is used, where quenching effects could potentially produce hard phases within the steel.

Other techniques have been practised on thin plate. Cutting through the deflection and then welding up the cut gap has been shown to be effective, but has the following drawbacks – it induces the processes of cutting, welding and dressing into the overall process. Welding a bead on plate X in the area of the deflection has also been found to be beneficial, but this cannot be used on visible areas of the structure.

The use of short coil induction heating has been found [4] to be capable of reducing thin plate distortion, without the drawbacks of the other processes described. A description of the process, its effect on plate properties and microstructure, and rework hours will be presented.

## 2 Induction heating process history and description

In the mid 1970’s, the Norwegian government funded a research project to counteract apparent risks to health when flame

***Fig. 1.*** *Main components of the Terac heating system.*

straightening steel structure. The eventual outcome of this was that the research team concluded that heating with induction was the best method. However, at that time the available induction generators were too large to be of practical application within shipyards. This led on to the development of equipment that was more suited to particular use in shipyards. The result of this was the production of the world's first air-cooled, transistorised induction generators. The equipment was called Terac, and were initially produced and sold in 1981 by members of the development team under their newly formed company (Elva a.s.). In 1996, Elva a.s. joined with FDF Freiburg, Germany, to form EFD Group.

The use of transistorised generators is now widespread, due to its lightweight nature and has applications in areas such as brazing, pre- and post-weld heat treatment, tube welding, hardening, annealing and curing.

As a result of this evolution, higher efficiency generators are now in use, but following the basic principles of rapid heating in easy to follow heating patterns. The induction heating process is generated when electrical eddy currents are induced into the work piece, and due to the resistance of the material, heat is generated within the affected area.

The induction heating process is generated when an electrical current is induced into the work piece. Eddy currents are formed, and due to the resistance of the material heat is generated within the affected area. The output power and shape of the induction coil determine size and depth of the heat affected area. The induction coil consists of a water cooled inductor through which the primary current flows. Actual power is fed to the induction coil from a transistorised frequency convertor, which in this instance normally runs at approximately 20 kHz. It has been established that the heat which is generated in the target area has an efficiency which is considerably higher than that of flame heating. In addition, the induction heating restricts the heat to a small well defined area, compared to the wider area generated by flame heating.

***Fig. 2.*** *Terac induction heating options:* ***(a)*** *Terac heating unit for straightening decks and* ***(b)*** *Terac heating unit for straightening vertical bulkheads.*

## 3 Equipment and operation

Although Terac has evolved since 1981, however the fundamental component types and working procedures remain the same:

### 3.1 Equipment

The equipment is housed in a standard sized (1.8 m) container for ease of component storage and transportation by crane or forklift within the work place, Fig. 1. The main components are:

☐ Frequency converter – mains voltage is converted to the correct frequency and current for efficient heating. The main parameters are set via the control panel and no operator adjustment is necessary after commissioning.

☐ Operator panel – common operator controls i.e. phase change (for cooling pump rotation) and fault indication & reset.

☐ Cooling system – is a closed loop tap water system.

☐ Capacitor unit – power conditioning prior to transformer at the heating unit. Operator-set timers integrated.

☐ 30 m – cable lead set between generator and capacitor unit

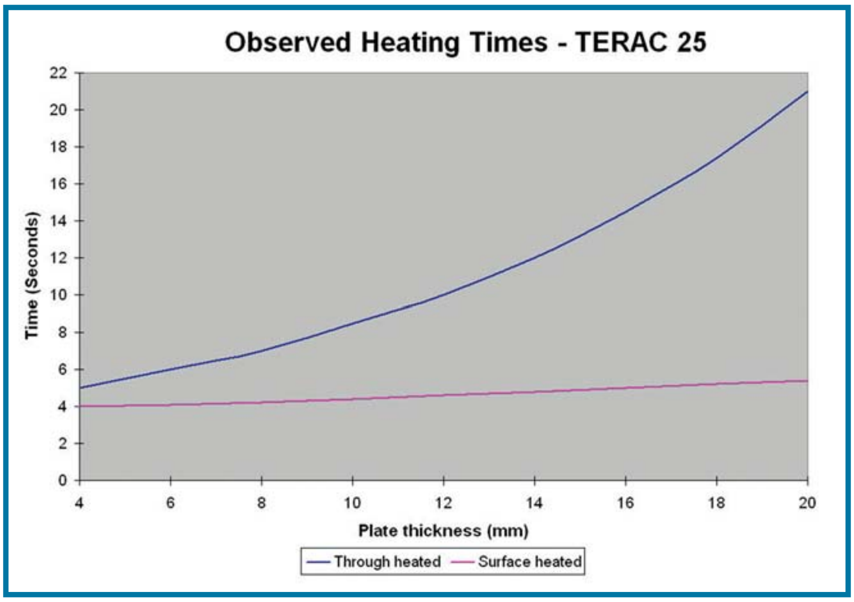

***Fig. 3.*** *Relationship among heating time, plate thickness and severity of heating.*

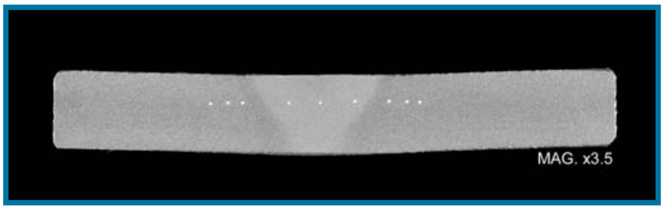

***Fig. 4.*** *Cross section of an area of heated plate showing the extent of heat penetration, with a very small proportion onto the bottom surface.*

***Fig. 5.*** *Comparison between induction heated deck area and conventionally straightened angled area on right hand side.*

(which can be increased to 45 m by the addition of an extension which doesn't affect parameter settings). This is shrouded with a heat and abrasion resistant material. This offers a 60 m maximum working radius from the base unit.

☐ Heating unit – includes inductor, HHT, electro-magnets (prevent movement during heating), operator control button and timer-select switch, Fig. 2.

☐ Hand-held heating attachment, Fig. 2 – for easier processing of vertical and/or tight spaces; a hand-held unit can be attached instead of the deck-heating unit.

### 3.2 Operation

The equipment is normally run off a 63 A power supply, and the only other changes to be made are related to the parameters for the specific plate thickness being treated. These heating times are very rapid based on the highly efficient induction heating process. In this specific application, the inductor heats a 160 mm length in about 4 s up to the Curie Point of steel (740°C), and the additional time required is based on through thickness heating of the plate. The relationship between plate thickness and heating time is shown in Fig. 3.

The heating creates an area in the plate which expands vertically and this can create a very slight ridge on the plate surface. However, in the instances where the ridge is evident, it is of little significance. Due to the vertical expansion and cooling contraction, tensile effects are produced which pull the plate into a flatter orientation. The greater the deflection, the greater will be the number of heating passes required to pull the area into tolerance. The extent of heat penetration into the plate is shown in Fig. 4, where a small proportion reaches the side opposite that being heated.

The Capacitor unit, Fig. 1, houses two timers, which can be adjusted by the operator. One is for normal heating and the other is for the heating directly behind the stiffener bar to counteract any heat sink effects.

The actual operation is started by placing the coil over the area to be heated and simply switching the power on. All aspects of the process are automatic after that. Thereafter the unit is moved to the next area to be heated and the operation is repeated. The heating pattern is a particularly critical component of the overall process. On a typical assembly, the longitudinal sectors would be processed before applying the same pattern to the transverse joints. If further straightening in some areas is required, further passes can be made in each zone. There are a number of techniques in use amongst existing Terac users; each operator has tried various patterns, sequences and heating times for their particular deck or bulkhead types before finding their preferred option. It should be stressed that there is little significant difference among operators.

A small number of Terac users cool the decks with water whilst straightening, however, when a sequence is applied which allows for each pass to be performed on cooled areas, force-cooling gives no increase in performance.

It is important to note that the assemblies to be heated must be fixed at the edges to provide the necessary restraint to allow the shrinkage effect to straighten out the deflections.

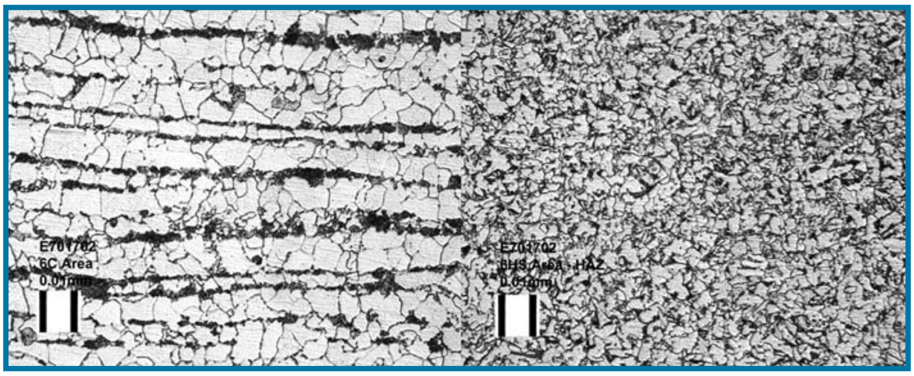

***Fig. 6.*** ***(a)*** *As rolled 6 mm thick DH 36 steel plate,* ***(b)*** *area of induction heated 6 mm thick DH 36 steel plate.*

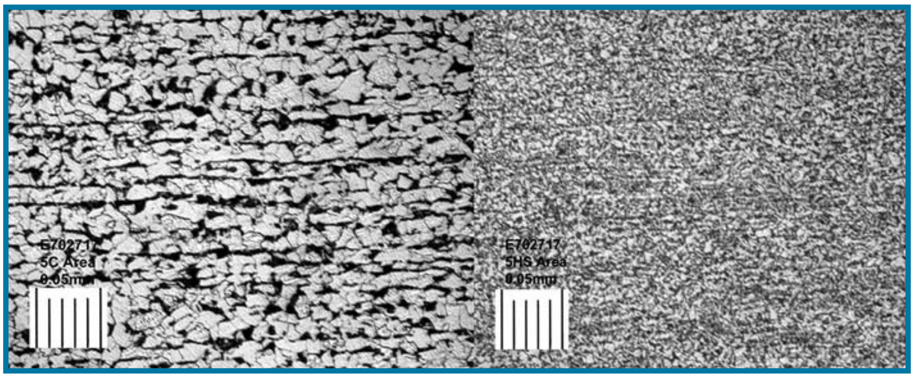

***Fig. 7.*** ***(a)*** *As rolled 4 mm thick DH 36 steel plate,* ***(b)*** *area of induction heated 4 mm thick DH 36 steel plate.*

## 4 Straightening performance

This section covers work carried out in a shipyard involved in the construction of naval vessels with a high proportion of thin plate in the structure.

A number of areas were induction heat straightened following a laid down sequence. Deflections on areas were measured before, during and after the induction heat straightening process. The induction heating process was compared against a standard, but well controlled, flame heating procedure. This procedure followed the laid down sequence used for the induction heating. In this specific area of the ship, the maximum allowable deflection was 6 mm. The evaluation consisted of establishing the percentage of the structure brought within tolerance. It should be noted that the intention was not to produce a perfectly flat structure, but one that was within the required tolerances. In this instance, the induction heating system achieved between 93 and 95% within tolerance, and the flame heating achieved between 51 and 56%. This consisted of both low and high deflections.

If the induction heating process is compared against the current straightening process which consisted of using studded aluminium strongbacks and controlled flame heating, which is the standard practice, then the time savings were estimated at about 75%. Other cost savings which could be incorporated into this were material costs (studs), strongbacks and process costs such as grinding off the stud scars and rewelding and grinding any undercut.

Fig. 5 shows an angled external area and a small external deck. The external deck was induction heat straightened and the angled external area was conventionally straightened. There is significantly more scarring and grinding on the angled area compared to the deck (the grinding here was not related to the induction heated process at all).

## 5 Material effects

When carrying out any heating process on steel plate, it is critical not to drastically alter the base material properties. It is for this reason that the heat affected zone (HAZ) adjacent to welds is tested as a matter of routine during welding procedure development.

In this specific work, three thicknesses of DH 36 steel were used (typical chemical analysis for each thickness shown in Table 1). The 4 and 5 mm thick plate was produced from the same mill, and 6 mm from a different mill. The differences in chemical analysis are related to specific mill characteristics, with the leaner chemistry being characteristic of the heavier rolling schedule for the thinner plate.

Plate material was treated in the same manner as the actual structure. Testing was carried out in these areas to determine material properties such as strength, toughness and hardness. In ad-

***Table 1.*** *Chemical analysis of the plates used in this evaluation (Lloyds Grade DH36).*

| Plate thickness | C % | Si % | S % | P % | Mn % | Nb % | Al % | N % |
|---|---|---|---|---|---|---|---|---|
| 4 mm | 0.131 | 0.174 | 0.010 | 0.019 | 1.27 | 0.011 | 0.034 | 0.0055 |
| 5 mm | 0.131 | 0.213 | 0.007 | 0.013 | 1.29 | 0.010 | 0.040 | 0.0046 |
| 6 mm | 0.167 | 0.34 | 0.010 | 0.017 | 1.44 | 0.024 | 0.039 | 0.0078 |

***Table 2.*** *Hardness measurements of heated and non heated plate areas.*

| | Induction heated | | | Conventionally heated |
|---|---|---|---|---|
| Plate thickness | 4 mm | 5 mm | 6 mm | 5 mm |
| Parent plate average hardness | 163 | 171 | 158 | 173 |
| Heated area average hardness | 183 | 182 | 182 | 202 |
| Hardness average difference | 20 | 11 | 24 | 29 |

dition, an evaluation was made of the steel microstructure in the treated areas and in reference areas of the plates.

For comparison purposes, a carefully controlled flame heating procedure was used on 5 mm thick DH 36 plate, following a similar pattern to that used for the induction heating. The comparison of strength and toughness revealed very little significant difference among the induction heated samples. There was a very slight drop in toughness in the heated areas, and a similar drop in yield strength (~ 7%). However in the flame heated areas there was a reduction in toughness of almost 45% and a 7% reduction in yield strength.

The hardness of the material did show some differences, as the localised cooling and heating of the area was inevitably going to change the steel microstructure in the area. Table 2 shows that there is between 6 and 15% increase in hardness of the induction heated areas compared to the parent plate material. For the flame heated material the increase was 16%.

The microstructures of the parent plate and the heated area are shown in Figs. 6 and 7, for the 6 and 4 mm thick material respectively. The parent plate structures all consist of elongated equiaxed grains of ferrite and some fine pearlite in the 4 and 5 mm thick plates. In the 6 mm thick plate the higher carbon content manifests itself with a higher level of pearlite in the structure.

The heated areas in all cases showed fine grained ferrite and spheroidised alloy carbides. This structure has been considered to be similar to a weld heat affected zone particularly that seen in the intercritical and subcritical regions of the HAZ.

## 6 Induction heating within a distortion reduction programme

When trying to reduce thin plate distortion in the shipbuilding industry, it is essential to tackle the problem at the source and not develop a rectification process that creates significant rework levels.

Within BAE Systems – Surface Fleet Solutions a programme of work has been carried out to tackle thin plate distortion at source [1]. However, there comes a point at which further benefits are difficult to achieve [2] without resorting to developing potentially costly solutions. Fig. 8 shows indicative benefits from an actual build situation where significant rework cost was avoided, but there was still a remnant portion there. In this case it has been considered to be more timely and cost effective to introduce a highly controlled heat straightening process in the form of Terac. It is conservatively estimated that this will further reduce the rework index by 50% from its current level. This is the only method currently available to gain such a step change at this stage of the build project. However, it does not mean that other work on refining the process using on plant trials and a combination of the finite elements method (FEM) [5] and artificial neural network (ANN) [6] will stop. The timescales on the other work are not short, whereas the timescale of introducing the induction heat straightening process is short.

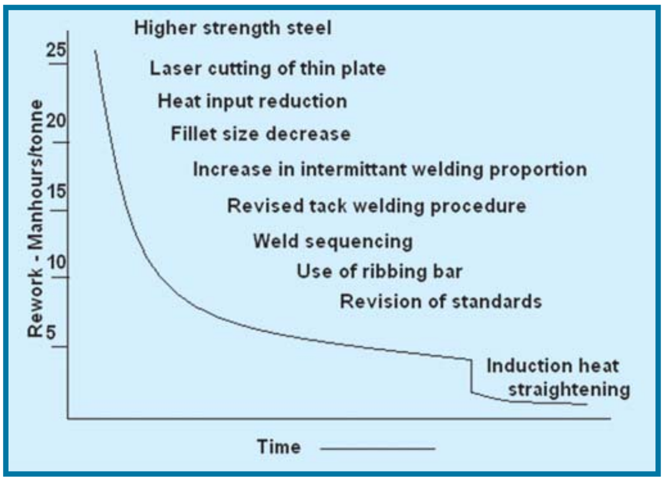

***Fig. 8.*** *Indicative data on reducing thin plate distortion rework and illustrating the potential benefit of introducing induction heat straightening technology.*

## 7 Concluding comments

The Terac induction heating system developed for the heat straightening of thin plate has been shown to be capable of bringing significant panel deflections within tolerance. When compared to an alternative method it was also shown to have superior performance. Examinations of heated areas in plate thicknesses down to 4 mm indicated that the process was not detrimental to the parent plate properties. There was a slight increase in hardness in the heated region when Lloyds Grade DH 36 was being tested.

**Literature**

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