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Weld Efficiency Factors Revisited

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Abstract

In recognition that pressure equipment welds that have not undergone a full volumetric inspection may contain internal defects, a weld efficiency is introduced. For spot volumetric inspection which is typically 10% of the weld length the weld efficiency is taken as 0.85. Of interest is that this factor is universally adopted in all known pressure equipment codes around the world. Its origins are obscure and to the authors' best knowledge, has gone unchallenged for the past 88 years. Additional interest is the use of 0.7 weld efficiency for a weld that has undergone no volumetric inspection. This is prevalent in many international pressure equipment code, but not all.

This paper revisits these factors. It considers how they were developed and explores a more rigorous probabilistic approach based on the amount of volumetric inspection and the likelihood of defects. It also considers the closely associated design factors. Understanding also that weld technology has developed since the early 1900 and in particular with the introduction of new technologies such as submerged arc welding, it may not be unreasonable to expect these weld efficiencies to differ from that initially developed. While the paper is not conclusive in its findings, it highlights there is justification to question the weld efficiencies adopted and proposes a program to develop more rigorous values.

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Keywords: weld factor; weld efficiency; weld history; probability.

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1. Introduction

To understand the introduction and development of weld efficiencies in pressure equipment design one must also understand the introduction and acceptance of arc welding as an alternative and eventual replacement of riveted

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construction of pressurized vessels. The use of the term arc welding is deliberate as joining of metals by forging had been a practice introduced over 1000 years ago (Anon [1]). The modern arc welding was ushered in by the developments in electricity and in particular, arc lights in 1881. From there development was rapid and Davy [2] notes that towards the end of the First World War, there was considerable interest in welded vessels but only for attaching branches. It was not until 1931, that the all-welded steel boiler drum was endorsed and this was constructed in accord with the newly released requirements of the Boiler Code of the American Society of Mechanical Engineers (ASME). Fish [3] reinforces this noting that fusion arc welding had been applied in the United States for the construction of pressure vessels since the 1910's and that *literally*[1] 1000's of pressure vessels had been fabricated during the interim period up to the 1930's. Fish goes further to note that the unreliability of welding resulted in numerous failures and obtaining insurance protection was problematic.

The introduction of fusion welding in the ASME Boiler Code of 1931 had its inception in the 1920's, (Anon [5]) being spurred along by the rapid use of fusion welding for pressure vessel fabrication and associated failures that ensured as a consequence. It is of particular interest that this would appear to be one of the first times that weld efficiency was defined; being the ratio of calculated membrane stress at the actual burst pressure to the stress of the parent metal as measured from tensile testing. To determine this ratio, vessels where fabricated and pressurised to failure. Anon [5] reports variation from as low as 60% through to 112% in weld efficiency for 25 welded vessels selected from a variety of fabrication shops, with double sided welds returning much more consistency with the lowest recorded as 90%.

Additional testing was also carried out on purposely welded vessels to introduce known defects. Welds were described as bad, poor, fair and good. A bad weld was a single sided weld with only 1/3rd penetration while a poor weld was also one sided but with 2/3rd penetration. It is not entirely clear, but it would appear a fair weld was welded both sides, but with incomplete penetration; apparently with a nominal 1/3rd lack of penetration in the centre of the plate. It is difficult to imagine how this was controlled. Nonetheless, results reported are seen in Table 1.

Table 1. Results taken from Anon [5].

Weld Quality	Average	Lowest	Greatest
good	102%	87%	115%
fair	85%	76%	96%
poor	51%	32%	65%
bad	43%	19%	61%

Notwithstanding the results of testing seen in Table 1, the committee of the day (Anon [5]) decided that the weld efficiency should be set at 80% and that all longitudinal welds would be doubled-sided V prep welds. It is also of interest that the factor of safety at that time, was 5, making the effective factor of safety as 5/0.8 = 6.25. It is important to note that at this stage, there was no mention of weld inspection other than visually.

There is scant reference to trace how the progress to full radiography of welds occurred. It is likely that concern was raised regarding the variation in results typified by Table 1, which varied from as low as 76%, if it is assumed that "fair" is taken as acceptable. However, by 1930, the modern principles of weld procedure qualification, volumetric inspection and stress relieving had been developed. This then led to the introduction of the ASME Boiler Code of 1931, based on the proving of the rules by destructive testing of a pressure vessel designed and fabricated to the new rules. Undertaken by Combustion Engineering (CE), it marked a significant event which saw CE been recognised with an historical landmark award (Anon [6]).

Fish also introduces the concept of weld classes; these being the highest, the middle and the lowest. As expected and consistent with modern construction, the highest requires 100% X-ray. Fish only gives the weld efficiency of the middle class as 80% and notes that it is higher for the higher class and lower for the lower class.

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[1] This is a direct quote from Fish [3]

Contributed nearly 80 years ago, Hodges [7] is definitive in his description of what is now considered modern welding and design practice. He notes that X-ray was developed to ensure welds were defect free and that post weld heat treatment was introduced to eliminate all fabrication stresses[2]. He also introduces weld qualification and the recognition that production weld coupons for higher classes of vessel were required. He notes that tests to destruction were undertaken on quite a number of vessels to establish the ASME Boiler Code principles. Finally, he notes that maximum weld efficiency granted under the ASME Code of the day for a fully X-rayed and heat relieved vessel was 95% which is not surprising. Acceptable defects under are significant and one example is given (Hodges [7]) of a slag inclusion running principally in the plane of the plate, as being acceptable if it is less than 1/3rd of the plate thickness. The acceptable thickness of this slag inclusion is not noted.

Hodges quotes residual stress measurements using strain gauges and a number of other techniques which regrettably Hodges does not describe, aligns surprisingly well with recent research. Stresses up to and beyond yield were measured. Fabrication is then concluded by undertaking a hydrostatic pressure test of 1.5 or even twice the design working pressure followed by magnetic particle inspection; all surprisingly modern.

At some point in time, the weld efficiency was upgraded from 95% to 100% for full radiography as it is currently (refer AS1210[8] and ASME[9]). More significantly we now have 70% for no inspection and 85% for spot inspection which is typically 10% of the total length of welds. While it may be reasonable to accept the use of weld efficiency of 100% if the weld is fully inspected, the use of 85% and 70% for 10% inspection and no inspection respectively could be questioned. Knowing that the basic premise for weld efficiency is the weakness of the weld compared to the unwelded parent metal; the weakness being due to inclusions, incomplete penetration and even cracking, there may be an historical basis typified by the results seen in Table 1 for setting these values. Whether it is reasonable to continue using these values is the purpose of this paper.

Nomenclature

C	Coverage for weld inspection (%)
l	Length of weld considered
n	Number of weld defects in a specified length
P_d	Proportion of weld containing defects (%)
R_e	Minimum guaranteed yield strength of material at ambient temperature
R_m	Minimum guaranteed tensile strength of material at ambient temperature
SF	Safety factor against ultimate tensile strength, typically 3.5 for a medium strength design or 2.4 or 2.35 for a high strength design
S_h	Membrane stress induced by hydrostatic test pressure
t	Plate thickness
T_{app}	The upper temperature for which the results of the hydrostatic test can be deemed applicable
x	Weld strength reduction factor = $(1-\eta)$
η	Weld efficiency factor
λ	Weld defect severity parameter
ρ -	Average density of weld defects (per length)

2. Review Approach

In reviewing the use of weld efficiencies, there are three key issues that require consideration. These are modern welding processes and practices, the improvement in inspection equipment and techniques and the use of hydrostatic testing as a tool to supplement inspection.

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[2] Direct quote from Hodge [7]

2.1. Modern welding processes

It is possible that with the higher level of automation compared with that in the past, defects are smaller and less frequent. Indeed it is possible that certain welding processes may be superior to others. For example, the authors are aware of numerous rhetorical statements that submerged arc welding rarely, if ever, results in weld repairs. Others note that the combination of a tungsten inert gas (TIG) root pass followed by metal inert gas (MIG), if any. The difficulty is to substantiate and quantify the claims and moreover to determine the residual risk that despite validation of the claim, the weld may still possess a flaw.

The first issue to substantiate that certain weld processes are superior to others will not be addressed here as it has the risk of creating unwelcomed controversy. However the development of a database of defect sizes that have been recorded by various fabrication shops and corresponding defect distribution would be useful. Given the data, it would be possible to undertake a stochastic analysis in order to quantify what the residual risk of a defect would be. This is reviewed in the following sections. Moreover, given there exists a risk of a defect, the sensitivity of defect size and defect distribution is also examined briefly in the following sections.

2.2. Inspection techniques and analysis of results

Methods of inspection are improving. So much so that the combination of phased array and time-of-flight diffraction (TOFD) is alleged to provide superior detection of defects; substantially greater than of X-Ray. It may be possible to develop a more rigorous stochastic approach to inspection whereby a given percentage of inspection can give increasingly greater weld efficiency. Indeed, there may arise a law of diminishing return and inspection above a certain percentage may be sufficient to ensure as close to 100% weld efficiency as is reasonable. This will be explored in what follows.

2.3. Hydrostatic pressure testing

Hydrostatic pressure testing has its roots in early riveted vessel construction. It detected leaks which were problematic due to the vessel construction and at the same time gave assurance of the vessel strength. It was continued into welded construction for similar reasons albeit one can reasonably question its need if the vessel is subject to both 100% volumetric inspection and post weld stress relieving.

That aside, if one is to explore the continued use of no volumetric inspection and ascribe a suitable weld efficiency, it may be possible to leverage on an enhanced hydrostatic pressure test to validate the integrity of the vessel. This will be reviewed in this paper.

3. Stochastic Review

It is reasonable to expect the aim of the codes would be to assure a similar margin on failure for the different inspection cases or at least to ensure this margin is not substantially smaller for the cases where spot or no inspection is done. The margins in the latter cases will depend on the severity and number of defects that remain after the fabrication and inspection is completed. Since these will vary according to fabrication process and the specific approach to welding it is difficult to derive completely general results. Here the aim is to provide some indicative comparisons to assess the extent to which margins may be different in practice.

The severity of weld defects can be modelled by statistical distributions. Exponential distributions have been used in several studies, see for example [01-02] and hence are taken as an approximation here.

For the case where the strength is reduced by (1-x) relative to the defect free case the cumulative probability that of shortfall for x is given by

$$F(x) = 1 - \exp\left(-\frac{x}{\lambda}\right) \tag{1}$$

where λ is the exponential rate parameter and $x = 1-\eta$ and is a measure of the number of defects and size. Order statistics considerations therefore indicate that the probability of shortfall for the worst of *n* defects is

$$G(x) = \left[1 - \exp\left(-\frac{x}{\lambda}\right)\right]^{n} \tag{2}$$

The average number of defects per length of weld is determined by the density ρ. Hence the above can be written as below considering a length of weld l.

$$G(x) = \left[1 - \exp\left(-\frac{x}{\lambda}\right)\right]^{\rho l} \tag{3}$$

In the case of no inspection, as per the code $\eta=0.7$ i.e.$x=0.3$, and G(0.3), will indicate the probability that the strength will be less affected. That is, the real efficiency will be larger than 0.7. It is reasonable that the code should expect a relatively high probability that the margin would be less affected than indicated by $x=0.3$ for this case. Here it is assumed that this probability is 99% or that there is only a 1% likelihood that the real margin will be less than that intended in the code. In which case, the actual efficiency will be smaller than 0.7.

For a given length of weld (l) the condition above is satisfied by combinations of defect density and severity (the latter indicated by the rate parameter). A wide range of densities may exist and the analysis here assumes densities in the range of 0.01 to 10 defects per metre. A total weld length of 15m (50ft) is considered.

The combinations of density and rate parameter satisfying equation (3) for the case of no inspection ($x=0.3$) are then considered for the case of spot inspection ($x=0.15$). The probability that the real margin (or actual weld efficiency) is less than intended by the code for these cases is summarised in Table 2.

The above results assume in effect no inspection and thereby no opportunity to identify defects and as might be expected, the probabilities for margins less than the code intent are higher here than for the $x=0.3$ case, where G(0.3)=99% and 1-G(0.3)=1%. The differences are substantial, particularly for the cases of higher defect density.

Table 2. Probabilities that actual $\eta < 0.85$.

Density (m^{-1})	0.01	0.1	1	10
G(0.15) %	95.6	88.0	67.5	29.2
1-G(0.15) %	4.4	12.0	32.5	70.8

The question now is whether spot inspection is sufficient to allow identification and hence repair of defects such that the margins are more aligned to the no inspection case. In the case of a density of 0.01 m^{-1}, i.e. 1 defect per 100 m on average, the likelihood of a spot inspection with a coverage, as per the code minimum requirement, of 150 mm per 15 m (1%) identifying any defect is very low indeed. Hence the inspection will have little impact on the probability estimated above. For this case the resulting likelihoods of the margin being less than the code intent would remain at approximately 4.4%. This may be considered reasonably close to the 1% value for the no inspection case. Hence the situation here may be considered reasonably comparable, even though the inspection has played little role.

As the defect density increases, so the probabilities for reduced margins become more significant and a greater inspection effectiveness would be needed to ensure alignment of the margins. It is therefore worth considering whether spot inspection is likely to be sufficiently capable in this respect. For the case of a defect density of 1 m^{-1} there is a 32.5% probability the margin is less than code intent. This can be reduced, however, if the inspection detects defects and follow up (repair) is performed. A pragmatic approach is to consider the inspection does not need to detect the worst defect to make an impact on the probabilities. A responsible approach to fabrication is to use inspection as a tool for process control such that detection of any defect would lead to process improvements which will change the margins. Hence the concern here is probability of identification (POI) of any defect rather than detection of the worst defect.

The POI can be estimated as per [11] as follows

$$POI = 1 - \frac{(100 - P_d)!(100 - C)!}{100!(100 - P_d - C)!} \tag{4}$$

When the density is 1 m^{-1} the POI is determined as 15%, i.e. the inspection has some, albeit limited, impact. The probability that the margin is less than code intent is therefore reduced and now is (1-0.15)×32.5 = 27%. This remains substantially higher than for the no inspection case.

The results above consider a weld length of 15 m only but similar trends are observed across a range of weld lengths. The results indicate that there is limited consistency between the spot inspection and no inspection cases. They suggest that there is potentially a large range of real margin depending on the nature of the welding defects and the choice of inspection approach.

4. Defects in welds

Leveraging on the concept that the basis for weld efficiency is that defects can exist in the weld such that the full strength of the plates being joined cannot be achieved, for a weld that is uninspected and as noted already, several pressure vessel codes (e.g. AS1210[8] and ASME[9]) allow the use of a weld efficiency, η of 0.7. The simplistic view is if $\eta = 0.7$, then the defect size could be as much as 0.3 times the plate thickness, t. Clearly there are other factors such as the shape of the defect in creating notch effects that intensify the stresses at the end and potentially causing unsustainable growth as the defects attempt to plastically relax the stresses.

4.1. Modelling Approach and Material assumed

The effect of defects was explored using the Abaqus Finite Element Analysis software, version 6.14-1. Although the defect could in principle exist anywhere within the weld, at this stage it has been taken as occurring only in the weld to parent fusion region. As seen in Fig. 1, the defect was placed in three positions; near the surfaces and central. It will also be noted that the weld preparation adopted is arbitrary and taken from AS1210 [8] and in particular Fig. 3.5.1.5(A) within that reference. At this stage the sensitivity of the defect to orientation and position within the weld has not been considered.

Three plate thicknesses were reviewed; these being 6, 16 and 40mm, albeit the thickest of the three is not permitted under pressure vessel codes that allow an uninspected weld. It is added to demonstrate the impact of thickness.

The material assumed was the Australia steel, AS1548-PT460 which has the guaranteed mechanical properties seen in Table 3. It was adopted as it is a commonly used carbon steel grade in Australia and is also similar to other commonly used carbon steel grade from other countries. At this stage, the sensitivity of the findings to material has not been considered.

Obviously the worst case defect is as long as the plate width and so for simplicity, a plane strain model was used. Again in order to gain a general appreciation of the problem, a flat plate or a plate with infinite radius has been assumed. Clearly the sensitivity to radius could be explored but it is felt unnecessary at this early stage.

Table 3. Guaranteed mechanical properties (refer AS1548[13]).

t (mm)	Yield (MPa)	UTS(MPA)	Elongation at UTS (%strain)
<16	305	460 to 580	21
>16 <40	295		

4.2. Tensile Failure

Of interest is the failure stress of the plates containing the defects. Here the elastic-plastic model as established via ASME Section VIII, Division 2, Annex 3.D (refer [10]) was adopted[3] and the load increased until the solution became unstable. Results are seen in Table 4. It is seen that the effective weld efficiency factor varies from 0.60 to 0.67; all less than the 0.7 assumed. While not surprising, it will almost with certainity be a function of the type of defect selected. Had the defect been selected with a more rounded shape, it is likely to have been closer to 0.7. Clearly the assumption of defect size being inversely related to weld efficiency, is incorrect.

Table 5 shows the same results as seen in Table 4 but now as a ratio of the allowable strength given by the application of AS1210[8]. The allowable is 133MPa for temperatures less 325°C and applying the weld efficiency factor, the effective allowable strength becomes 93MPa.

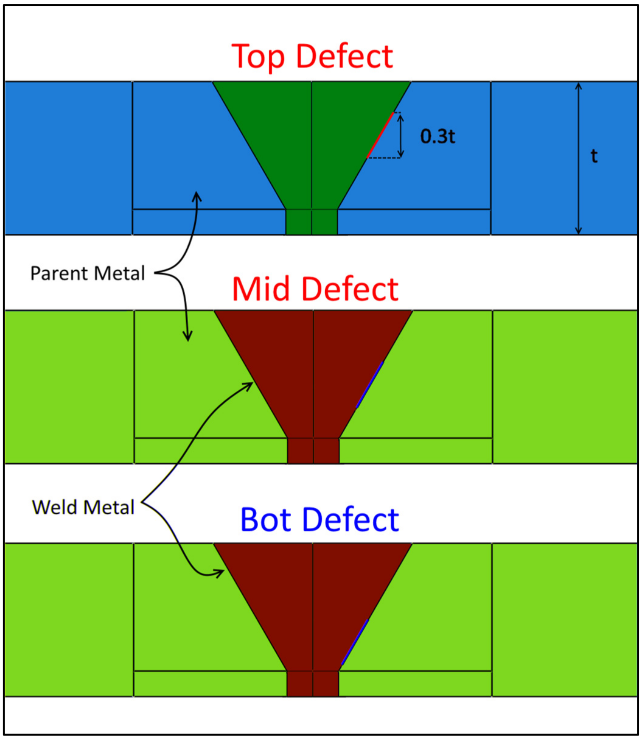

Fig. 1. Defects modelled.

Table 4. Results of stress at failure normalised to the no defect case for each thickness.

Defect Location	t = 6mm	t = 16mm	t = 40mm
No defect	1	1	1
Central	0.65	0.63	0.65
Top	0.62	0.61	0.63
Bottom	0.61	0.60	0.64

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[3] Clearly other codified approaches could also be used. This was selected only due to the authors' familiarity with the Code used

Table 5. Results of stress at failure normalised to the allowable strength (133×0.7 = 93MPa).

Defect Location	t = 6mm	t = 16mm	t = 40mm
No defect	4.91	4.89	4.39
Central	3.17	3.10	2.87
Top	3.05	2.99	2.76
Bottom	2.98	2.95	2.79

It will be seen and as would be expected, results for the 6mm and 16mm plates are similar while for the 40mm plate it is notably less, being principally due to the reduction in material properties. More importantly is that the failure as a ratio to allowable is now less than 3.5 which is the target required by AS1210[8] and ASME[9] for medium strength design and supports the recognition of the reduced weld efficiency as already identified in Table 4.

4.3. Relationship of Weld Efficiency to Defect Size

It was pointed out that the simplistic relationship of weld defect size as being related via the expression $(1-\eta).t$ is approximate and dependent on a range of factors. For the defect type and orientation adopted in the study, the projected length of the defect as seen in Fig. 1 was varied and the effective weld efficiency established. Results are seen in Fig. 2. While the relation is nearly linear, at least for the defect to thickness ratio greater than 0.05, it varies and given the variation, the notional relationship given by $0.7(1-\eta).t$ would seem reasonable. This is of course a loose relationship and offered only as a guide.

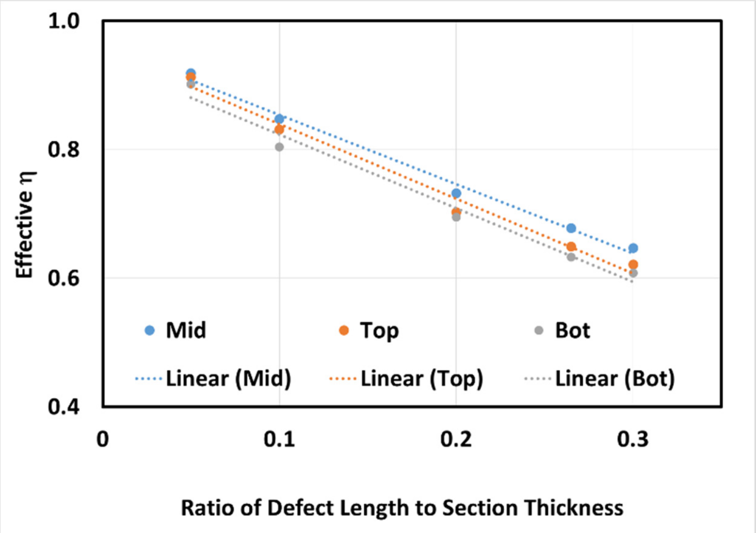

Fig. 2. Relationship of weld efficiency to defect size.

4.4. Hydrostatic Pressure Testing

As noted previously, hydrostatic pressure testing has the dual purpose of final validation of weld strength and also establishing leak tightness. Except in certain cases such as some stainless steel vessels, it is rare that the hydrostatic test pressure raises the wall stress to cause any significant distress. Indeed ASME[9] requires only 1.3 times the design pressure which understanding that corrosion allowance increases the wall thickness as well as the necessary rounding to available plate sizes, will result in quite low stresses at hydrostatic pressure. The proposal is being explored to ultilise hydrostatic pressure testing as a means to suspend volumentric inspection.

The proposal then is to assume a value for η, in this case 0.7, and determine the required hydrostatic test membrane stress, S_h, as seen in equation 5.

$$S_h = 0.95\eta R_e \tag{5}$$

The use of 0.95 in equation 5 is to ensure distortion does not occur. The corresponding hydrostatic test pressure can then be determined. The concept is to potentially distress any defects in the welds and so prove the assumed efficiency. The difficulty here is measuring if distress has occurred. Provided rupture does not occur which is unlikely, small localised distortion will be readily be detected. Nonetheless for static vessels, this should not be an issue.

Seen in Table 6 is the results of simulating, using Abaqus software, a sequence of loading steps applied to the defective welds and the material and plate thickness used in the previous section. The sequence was to load to the hydrostatic pressure using equation 1, reducing to no load and then to finally load until failure.

The effect of loading to hydrostatic pressure has resulted in local yielding and so on relaxation of the load, residual stresses remain. The question being explored is if the hydrostatic testing would result in unacceptable damage and in effect reduce the plate remaining strength. An example of the residual stress remaining after removal of the loads is seen in Fig. 3.

Table 6. Stress at failure following hydrostatic pressure test, normalised to the allowable strength.

Defect Location	t = 6mm	t = 16mm	t = 40mm
No defect	4.90	4.91	4.37
Central	3.30	3.10	2.77
Top	3.12	2.93	2.71
Bottom	3.15	2.95	2.70

Comparing Tables 5 and 6, hydrostatic testing does not appear to cause damage. Stresses at failure are similar with or without hydrostatic testing.

A check was also undertaken to verify that continual loading from no load to full design load would not result in ratcheting.

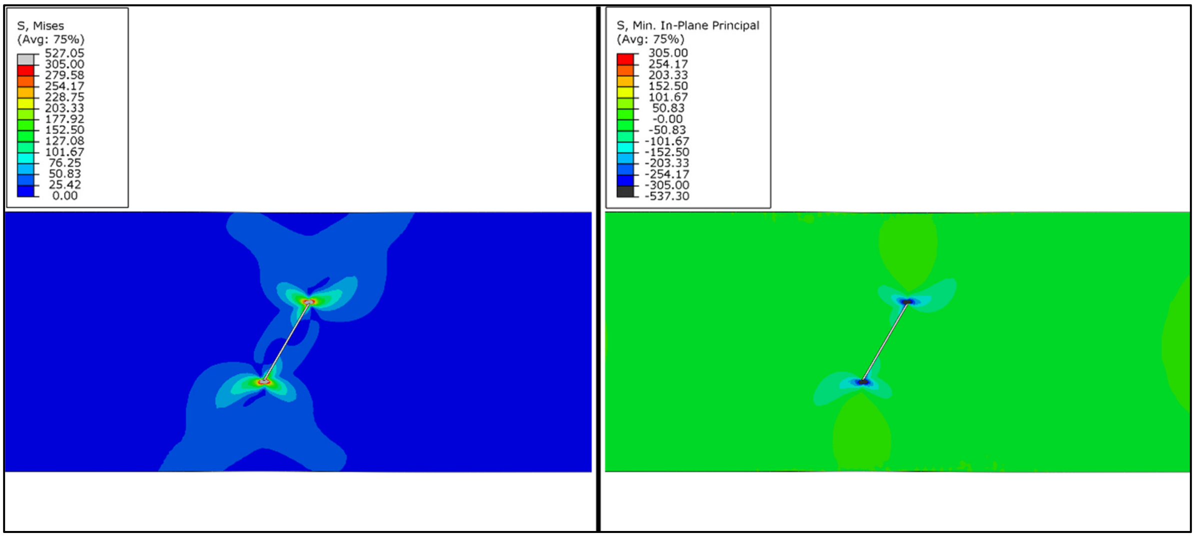

Fig. 3. Residual stress in 16mm plate after removal of hydrostatic load.

5. Discussion

The purpose of this paper is to open up the debate on weld efficiency. It has essentially lay dormant for some 80 years with only the uninspected weld efficiency being adjusted from 0.65 to 0.7 in that time. It is demonstrated that it is possible to prove the weld by selecting a hydrostatic test pressure that increases the stresses to near minimum guaranteed yield. If a defect existed and the actual material was at minimum yield strength, local distortion would occur and possibly rupture. Temperature effects aside, all pressure vessel codes have an allowable strength given as the minimum of $R_e/1.5$ or R_m/SF. For the common construction material of carbon steel typified by AS1548-PT460 and used as an example in this paper, a successful hydrostatic test using the pressure given in equation 1, the guaranteed design margin will be $0.95\times1.5\times SF\times R_e/R_m$ or 3.3. This is based on R_e of 305MPa, R_m of 460MPa and SF of 3.5. Also understanding that the material properties are more than often better than the minimum guaranteed yield, the margin would be greater. The residual stresses remaining are not disruptive and indeed may be helpful in relaxing weld induced residual stresses. The question remains is what weld efficiency should be adopted depending on the level of inspection. Currently at least two pressure vessel codes (AS1210[8] and ASME[9]) permit the use of uninspected welds but only for medium strength design. The selection of 0.7 has an unclear historical basis and no substantiation for its selection was apparent in the authors' literature search. Weld technology has advanced substantially since the introduction of this efficiency factor so it is reasonable to reconsider if 0.7 remains appropriate. The option offered here is to consider the use of an extreme hydrostatic pressure to prove that the weld has the designated weld efficiency. This could offer a new class of vessel and one that is proven by hydrostatic pressure testing. This upper temperature will be referred to as the applicable temperature or T_{app}.

This may be as low as 120°C. There will also be a restriction on fatigue and in general, it should be restricted to truly static pressure vessels. So in principle, if a fabricator can demonstrate that their weld process can consistently produce a defect free weld with a maximum level of uncertainty in possible defect, they can elect a weld efficiency based on that uncertainty and so apply equation 1 to prove that the vessel is sound without recourse to volumetric inspection.

In addition to restricting the design temperature to T_{app}, there will also be the need to impose a lower design temperature. A successful hydrostatic test will ensure that the material has adequate material toughness to ensure protection against brittle fracture and fracture toughness reduces with temperature. As such, ideally the lower temperature should be set by the hydrostatic test temperature. It will be possible however to assess the sensitivity of the material fracture toughness with temperature and reduce the lower temperature. This will need to be considered in more detail.

The process required to be undertaken by the fabricator to ensure the nominated weld efficiency is being maintained may require routine testing either via a weld production plate process or simply ongoing weld qualification. The frequency will no doubt be related to the vessel risk to be accepted and this will be discussed later. This will be a crucial aspect and will require debate.

Overarching this discussion is that in addition to a weld efficiency there is also a design margin. As already discussed this design margin is built into the allowable design strength. Seen in Table 5, even with a defect, the effective design margin against plastic collapse is still significant, albeit this should be tempered with the understanding that the review at this stage is restricted to T_{app} and static duty. So even with a significant defect the safety margin against plastic collapse remains considerable. For a truly static vessel with a design temperature less than T_{app}, if the defect is greater than the corresponding weld efficiency assumed, there will still remain a margin of safety. Indeed it can be argued that a margin against yield is all that is required for a truly static vessel.

An important point to make here and already muted, is that even given the margin against plastic collapse, it is possible that the defect may be such that it is on the point of failure by brittle fracture. This raises an interesting point for discussion. Given that vessels have been manufactured for many years under a no inspection arrangement, it is possible that there are vessels in operation that have a minimum safety factor which in principle may only just exceed 1. Industry has inherently accepted this over the years. One could then reasonably ask what the consequence of this is. The purpose of safety factors is to guard against this very thing. Philosophically, if there is absolute confidence in the loading and integrity of the product both during manufacture and later operationally, there is little point imposing a safety factor much greater than 1. The emphasis here is on the use of "absolute". Provided one can be assured that the hydrostatic pressure test will introduce the greatest loading, it will test the weld and so demonstrate a factor greater than 1 against brittle collapse. How much greater will be governed by several factors. This is an important area for further work.

The term weld reinforcement[4] was introduced deliberately in the early stages of welding development and was to provide a means of addressing any imperfections in the weld. Early testing (e.g. Table 1) leveraged on this. Modern welding practice is not to remove this reinforcement unless there are specific reasons. As such, as it was in the early formative welding years, this is additional reserve available to address any imperfections in the weld. This was not explored as part of this paper as it was intended to consider only the worst possible weld configuration. Indeed to conceive a weld with a defect some 30% of the thickness would be untenable in this modern era and lends credence to reviewing the factor. That said and already discussed, the need for welding quality control and measures to demonstrate ongoing compliance with the weld quality must be integral to the process. Finally, in the fabrication of pressure vessels, it is unlikely that the practice of undertaking hydrostatic pressure testing will ever be ceased and the proposal made here is to enhance its use to also validate the weld efficiency assumed in lieu of volumetric inspection.

For vessels having some level of inspection, it is possible to impose a weld efficiency based on level of risk to be accepted. Defining the appropriate levels requires further work however, taking into account the likely defect distributions and the POI for different inspection coverage. The approach covered in Appendix D of [11] could form the basis for further development in this area.

6. Conclusions

This paper has explored the origins of weld efficiencies used in the design of pressure equipment. In doing so it offers a number of proposals and these are expanded below and offered as conclusions:

(1) Aside from successful 100% volumetric inspection with the corresponding weld efficiency of 1, the origins of the weld efficiency correlation to reduced inspection is lost in history. Of the most interest is the use of 0.7 weld efficiency by some pressure vessel codes for no volumetric inspection. There is no mention of how this was determined.

(2) The basis of the weld efficiency is to account for defects that result in reduction of effective cross section through the weld as compared with a weld that has no defects. The relationship of weld efficiency to defect size is complex but is notionally given as $0.7(1-\eta).t$. This is approximate at best.

(3) Based on a fabricator established η, it is possible to establish a class of static pressure vessels with a design temperature less than T_{app} but greater than that is based on hydrostatic pressure testing rather than inspection. This requires further in-depth considerations particularly in consideration of minimum operating temperature.

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References

[1] Author Anonymous, "Extract from a thesis", http://libback.uqu.edu.sa/hipres/Indu/indu10740.pdf.
[2] Davy, D.H (1935) "The welding of boiler drums and other pressure vessels", Symposium on the Welding of Iron and Steel, Vol 1, pp205-214

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[4] Weld reinforcement is the build-up of weld material that results in additional thickness at the weld

[3] Fish, E.R (1935) “Welded pressure container construction in the united states”, Symposium on the Welding of Iron and Steel, Vol 1, pp227-231.
[4] Moses, A.J (1932) “Practical application of the A.S.M.E welding code”, Journal of the American Welding Society, p11-
[5] Anon (1923) “An investigation of welded pressure vessel”, Journal of the American Welding Society. 2 No 5:11-162, 1923. Reprinted as Bulletin of the American Bureau of Welding, No 5 June 1923, 152pp
[6] Anon (1980) “A National Historic Mechanical Engineering Landmark - The C-E All Welded Test Boiler Drum”, Dedication Program. May 2
[7] Hodges, J. C (1936) “The Welding of Pressure Vessels”, Journal of the American Society for Naval Engineers, Vol 48, Issue 4, pp498-522
[8] AS1210 (2010), “Pressure Vessels”, Standards Australia.
[9] ASME Boiler and Pressure Vessel Code (2013), “Rules for Construction of Pressure Vessels”, Section VIII, Division 1, 2013
[10] ASME Boiler and Pressure Vessel Code (2013), “Rules for Construction of Pressure Vessels”, Section VIII, Division 2, 2015
[11] HSE RR 454, Probability of Detection (POD) Curves: Derivation, Applications and Limitations, UK Health and Safety Executive, 2006.
[12] Methodology for Estimating Fabrication Flaw Density and Distribution – Reactor Pressure Vessel Welds, NUREG/CR-6989, US Nuclear Regulatory Commission, 2006
[13] AS1548(2008), “Fine grained weldable steel plates for pressure equipment”, Standards Australai