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# Thermographic assessment of thermal cycle influence on structure and properties of the 4430V steel

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**Abstract**

When creating welded joints, a specified amount of heat is delivered into the welding area and a so called heat-affected zone (HAZ) is formed. The key issue is to reduce the width of the HAZ, because properties of the material in the HAZ are worse than in the base material. To achieve that precise control of process temperature is demanded, while it determines the type of metallurgical transformation. Obtained results prove that features extracted for sequence of thermographic measurements can be a good tool for estimating the properties of material in heat affected zone.

## 1. Introduction

The 4330V steel is a material with high strength and plastic properties and it has a structure of tempered martensite (Fig.1). It belongs to the group of low alloy steels with improved strength properties. In its chemical composition there is an increased carbon content of 0.31% and small addition of chromium, nickel and molybdenum. The main micro-additive is vanadium, thanks to which the 4330V steel achieves such high properties. High strength and plastic properties are also due to the appropriately performed heat treatment consisting of hardening in a water bath with a temperature of 890°C, then the material is subjected to high tempering at 620°C and stress relief to reduce stresses at 605°C. Due to the high carbon equivalent of around $C_e$ = 0.89, it is a hard-to-weld steel that requires proper heat treatment before and after welding in order to maintain high properties. According to that in practical application control of welding process temperature, that influences the amount of energy delivered to material and leads to speed of cooling, that is crucial for control of metallurgical transformations. The peak temperature of welding has a significant effect on the strength, toughness and other mechanical properties because of the change in the prior austenitic grain size and precipitation behaviour. For instance, grain coarsening can occur [4], precipitates can dissolve [5]. To minimize the brittle zone, the evolution of martensite-austenite constituent and consequent change in hardness in the HAZ has been studied [6-8]. Additionally, when hardness changes, the impact strength of material is also affected.

The main issue connected with the precise measurement of temperature is connected with the need to set exact emissivity value. It is commonly known, that even small error in the emissivity setting can lead to large error in temperature measurement. When there is no possibility to use e.g. two colours system, where setting of emissivity can be omitted, other approach, that can build a link between measured or calculated feature value and transforms that took place in the heated zone is required. The main advantage of this type of method, is that the mistake in emissivity selection would less affect the result measurement and finally the result of properties assessment.

In the paper descriptors taking into consideration temperature distribution in the heat affected zone, were used to assess properties and microstructure of the 4330V steel in the result of simulated thermal cycles application [1,2].

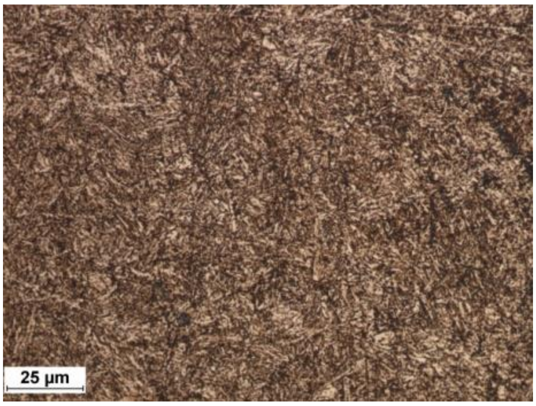



***Fig. 1.*** *Microstructure of the 4330V steel*

## 2. Geometric assessment of heat distribution

In order to determine the temperature that was generated during welding (in real situation or during simulated thermal cycle) image processing procedure has been proposed. Key assumption was, that with increase of amount of heat delivered to a joint the region around the joint with increased temperature will grow. The main stage of processing algorithm is the thermogram thresholding (Fig.2). This process is made according to normalized temperature, where min-max range of the normalization process is chosen arbitrary for the whole set of possible welding procedures (assuming values of minimal and maximal temperature, that can occur during welding).

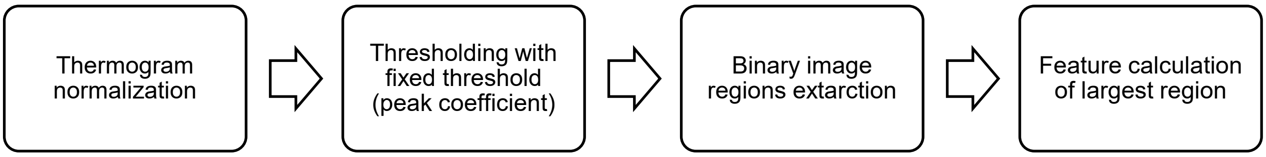



***Fig. 2.*** *Idea of thermogram processing*

There were several stages of processing chosen according to the maximal temperature selected for all process realization. Peak coefficients were 30%, 40%, 50%, 60%, 70%, 80%, 90% of the highest temperature For lower values regions obtained in binary images (BW) were larger, while for higher, regions were smaller. Shape of binary region changes in time during the heating and cooling phase. Exemplary set of BW images extracted from thermograms for the peak coefficient 40% (Table. 1). It can be seen that in the initial phase of heating, temperature increases around the axis of joint (Fig. 3). Then further increase of temperature runs almost symmetrically on both side of joint. This heat distribution is same as it is in the case of real welding processes, like TIG or GMA. In those cases, the central part of the a joint is the hottest. On both sides of it, HAZ is formed, and the width of this region depends on welding energy, welding speed, welded material and other parameters of welding process. In the investigated case, when maximal temperature is reached, cooling process begins. For a homogeneous material structure, the process goes near identical on both sides of a joint. Also looking only on BW images taken on the laboratory upset welding machine, the difference in duration between start and run out is visible only on the basis of temperature distribution shape.

This approach can be applied on-line, because it can be realized on simple PC computer. The method can be done with logical indexing, thus there is no need for high computational power.

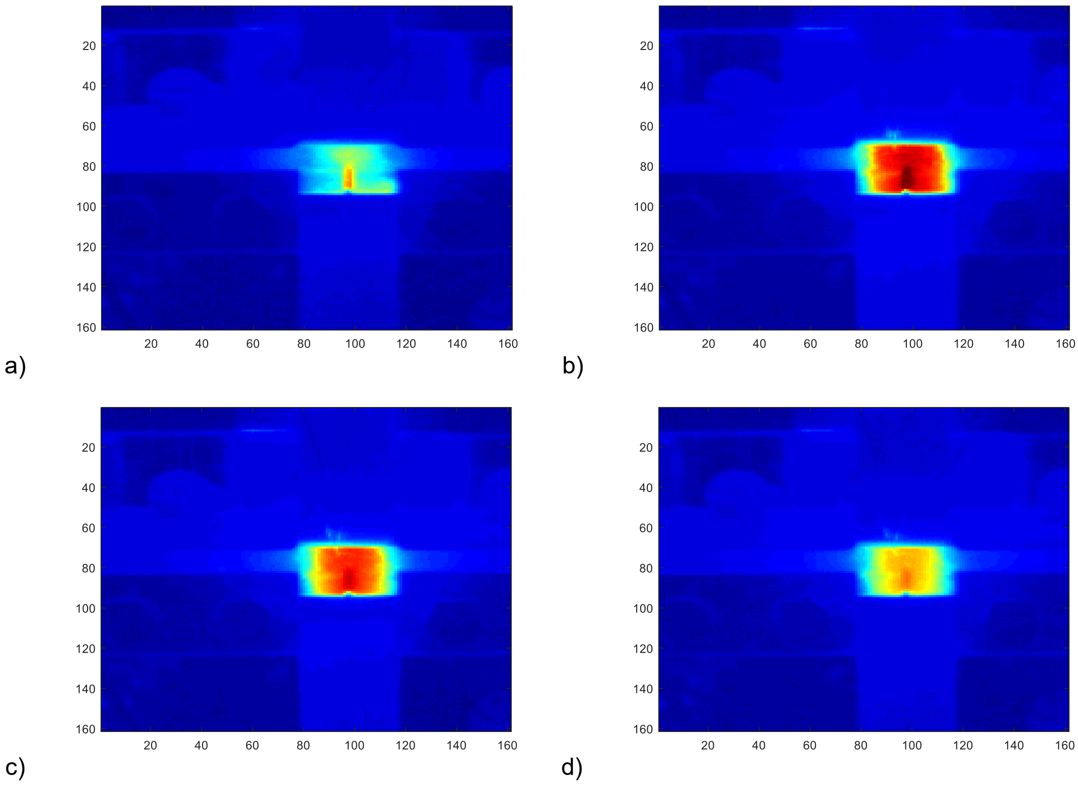
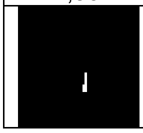
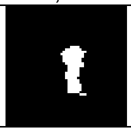
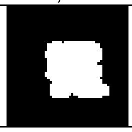
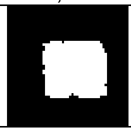
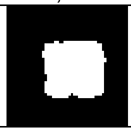
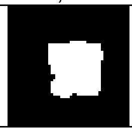
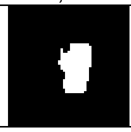
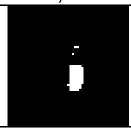
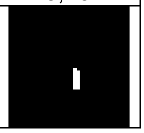



***Fig. 3.*** *Heat distribution for heating time (sample ID 20): a) 2,36s, b) 3,56s, c) 4,76s, d) 6,36s*

***Table 1.*** *Evolution of heat distribution (sample ID 20)*

| Time [s] | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 2,36 | 2,76 | 3,16 | 3,56 | 3,96 | 4,76 | 6,00 | 6,36 | 6,76 |
|  |  |  |  |  |  |  |  |  |

Obtained regions were assessed using various geometrical features. Most valuable of them where:

- Area – number of pixels in the BW region;
- Convex Area – number of pixels in the convex image (specifies the convex hull, with all pixels within the hull filled in) generated for the current BW region;
- Equivalent Diameter - diameter of a circle with the same area as the region;
- Extent - ratio of pixels in the region to pixels in the total bounding box;
- Perimeter - Distance around the boundary of the BW region;
- Solidity - Proportion of the pixels in the convex hull that are also in the region.

## 3. Case study

Suitability of proposed approach was verified on the basis of data gathered during an active experiment, where different thermal cycles were simulated and sets of thermograms were acquired.

### 3.1. Experiment procedure

In order to gather research data an experiment using a specially constructed bench equipped with a resistive heating source dedicated to simulation of a thermal cycle using an indirect method was carried out (Fig.4a). Simulation of welding heat cycles allows to determine the material behaviour in a critical temperature range 800-500°C, where adverse structural changes occur. An uncooled infrared Infratec HR Head camera connected to the PC with installed acquisition and control software was used to observe tested specimens during heating and cooling (Fig 4b). The IR camera had a resolution of 640×480px and was able to acquire images with a frame rate of 50 fps. The temperature range of simulated heating and cooling cycles in the air, carried out during the process, ranged from 300 to 1200°C (every 100°C). More than 50 sequences were taken, but only 35 of them were used for further studies. The heating times of the samples were in the range of 2-7 seconds. Nevertheless temperature of process was monitoring during experiment, later it was found, that because of samples thermal interia and manner of welding machine control, there were some uncertainties in process monitoring data.

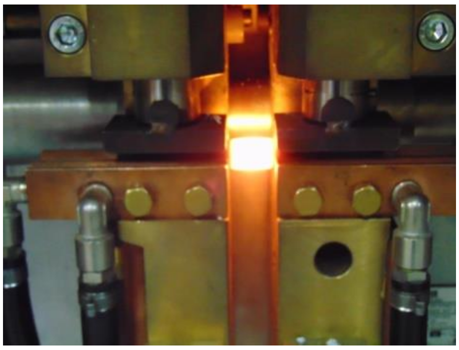


***Fig. 4.*** *Stand for upset resistance welding – view of the heated specimen*

Knowing maximal heating temperatures and time of cooling on the basis CCT (continuous cooling transformation) diagrams a set of point features was used to assess the sequence of thermograms and according to that estimate the structure being the result of welding process. Additionally all features were selected to minimize uncertainties being their result of errors in emissivity setting. Sensitivity of various features make proposed approach more suitable for industrial application as it is in case of measuring of specimens temperature with thermocouples, because there is limited information about geometrical properties of HAZ.

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### 3.2. Results

From all gathered thermogram sequences those with real peak temperature in range 375°C - 1300°C were selected. Temperatures for consecutive specimens were as follows: 1 - 375°C, 2 - 440°C, 3- 640°C, 4 - 610°C, 5- 650°C, 6- 570°C, 7- 640°C, 8 - 670°C, 9 - 680°C, 10 -640°C, 11 - 700°C, 12 - 800°C, 13 - 790°C, 14 - 700°C, 15 - 840°C, 16 - 910°C, 17 - 900°C, 18 - 890°C, 19 - 850°C, 20 - 1050°C, 21 - 950°C, 22 - 1090°C, 23 - 900°C, 24 - 1150°C, 25 - 1100°C, 26 - 1070°C, 27 - 1110°C, 38 - 1220°C, 29 - 1250°C, 30 - 1180°C, 31 - 1250°C, 32 - 1300°C, 33 - 1270°C, 34 -1200°C, 35 - 1300°C Those samples were processed using thresholding procedure described in sec. 2. The range of temperatures used for normalization was between -40°C and 1400°C. This range was chosen for emissivity setting ε=0,85. After preliminary studies only equivalent diameter and convex area were chosen for further research as most sensitive features.

All specimens undergone tests of mechanical properties. Two most important properties were measured, namely hardness and impact strength. It was found that in general mechanical properties in the HAZ are close to those of base material when heating temperature did not exceed 700°C. This phenomena is clearly visible in Fig. 5. For sample ID 11 the impact strength is close to the impact strength of base material.Comparing this with convex area features, it was revealed, that rapid growth of area is connected with decrease of impact strength. Rise of high temperature region area is bounded with the increase of temperature in joint (heating area). In Fig. 6 microstructure of two specimens is presented. It can be noticed that low temperatures affect the microstructure in marginal way and properties of such structure are near the properties of base material, what is wanted in terms of assuring high quality of welded joint.

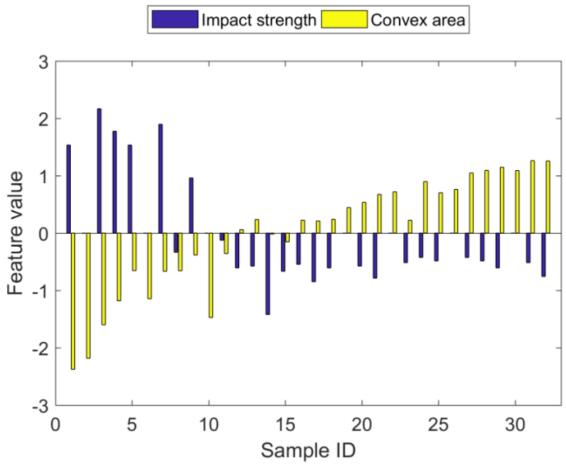
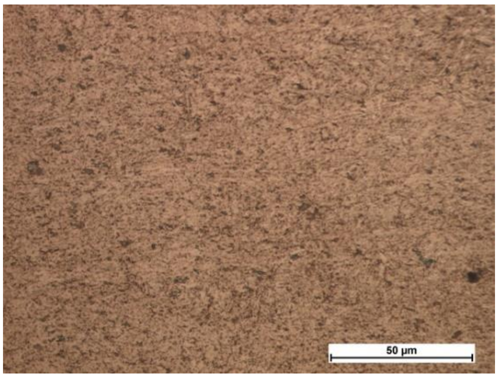



***Fig. 5.*** *Comparison of normalized impact strength and convex area*

a) 

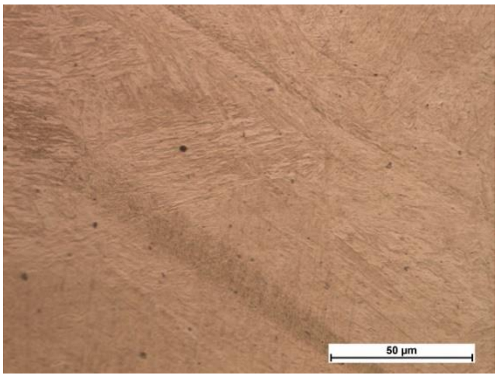
b) 


***Fig. 6.*** *Structure of 4330V steel heated to: a) 350°C, b) 1200°C*

Having the features distribution for all peak coefficients selection, an additional experiment has to be performed. Taking into consideration value of peak coefficients should be selected. In Fig 7 area of increased temperature is gathered for one sample (ID30). Comparing the heating and cooling zone with a result collected by use of a thermocouple, a conclusion can be drawn, that the cooling zone is different form the ideal one. To state which percent value is the most informative one, point features were benchmarked against vector of impact strength values.

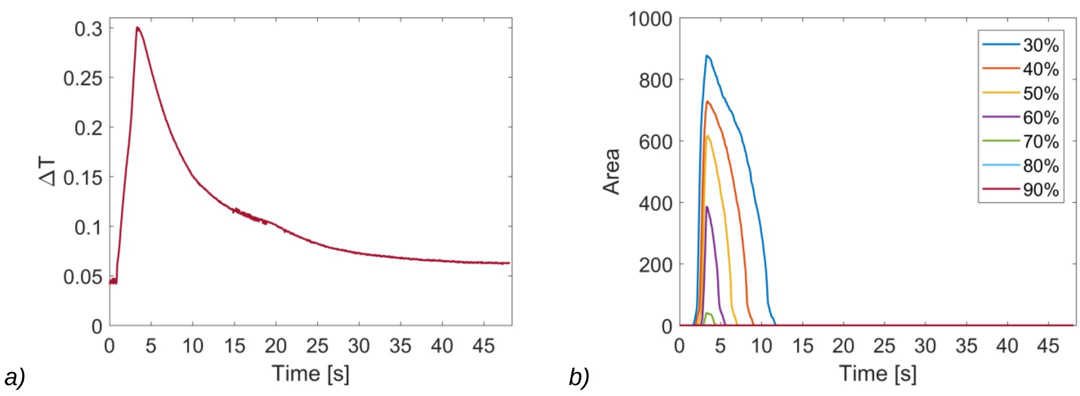



***Fig. 7.*** *Sample 20 (1050°C): a) normalized temperature, b) area of different temperature regions*

Cross correlation values between impact strength and geometric feature value for different peak coefficients are collected in tab. 2. It was found that lower values of peak coefficient are more beneficial, because of high dependence between feature and real temperature values and distribution.

***Table 2.*** *Correlation between mean feature values and specimens impact strength*

| Feature type | Peak coefficient | | | | | | |
|---|---|---|---|---|---|---|---|
| | 30% | 40% | 50% | 60% | 70% | 80% | 90% |
| Convex Area | -0,7921 | -0,7648 | -0,6587 | -0,4669 | -0,3397 | -0,2796 | -0,2433 |
| Equivalent Diameter | -0,7687 | -0,7930 | -0,7717 | -0,5600 | -0,3778 | -0,3084 | -0,2620 |

In Fig.7 a straightforward link between the peak coefficient and feature value can be found. To decide not only if heat generated in welding process affects basic mechanical features, but also estimate the value of mechanical property, distinguishing between results obtained for all specimens should be assured. Analysing obtained results in most cases highest difference between feature distribution and peak coefficient were obtained for peak coefficient of 50-60%. In those cases gradient of feature value increase is highest. Also relative difference between feature values for two consecutive values of peak coefficients can used to quantify the quality of made joint. Convex Area feature being most correlated with impact strength Is also best, when trying to distinguish process condition analysing changes of feature values. It can be also noticed that for higher peak coefficients feature values for samples with lower peak temperatures were are equal to zero. It is caused by the normalization process.

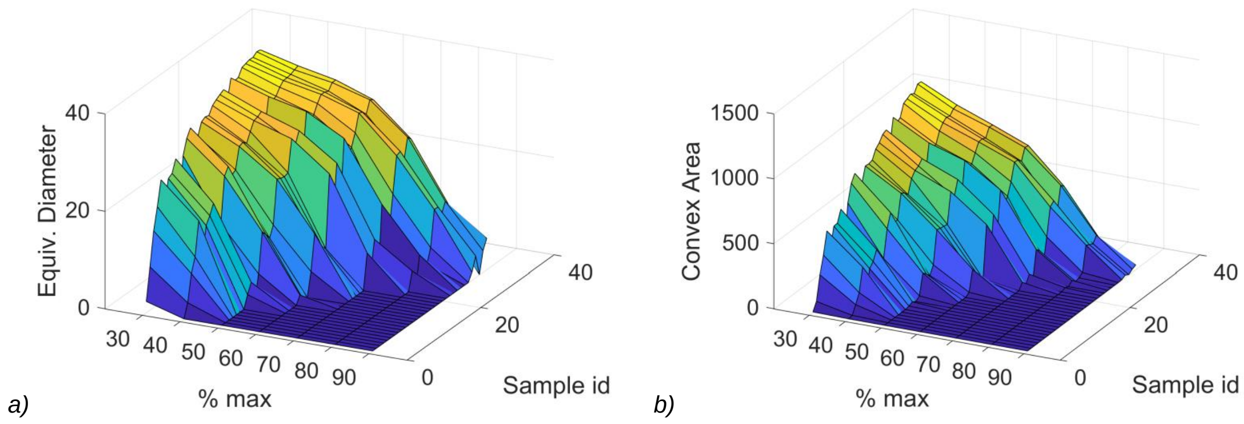



***Fig. 8.*** *Sample ID 20 (1050°C): a) equivalent diameter , b) convex area in function of peak coefficient and sample identifier*

Mean correlation between maximal temperature in joint and impact strength calculated for all available data sets is -0,8132. According to that a negative correlation between those quantities is high, so increase of process temperature is causing decrease of impact strength, what is an unwanted phenomena. Nevertheless, in the presence of unwanted temperature artefacts causing rapid drop of temperature generalization of possessed knowledge require application of 3d curve fitting methods.

## 4. Conclusions

Performed preliminary studies prove that features extracted for sequence of thermograms can be used to determine how steel behaves during rapid heating and cooling as well as, what structural changes occurring in the material, especially in heat affected zone. Geometrical features like convex area and equivalent diameter calculated for potential heat affected zone can be successfully applied for estimation of common mechanical properties of metal material (especially alloyed steels). It has been also found, that if significant change of mechanical parameters is caused by exceeding some temperature, the link between feature value like area of heated region and e.g. impact strength is strong. Elaborated parameters can be used to control, e.g. upset resistance welding, in order to obtain narrow HAZ, with parameters closest to those of base material. Further studies will cover issues connected with possibility of on-line prediction of microstructure of a material.

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