

Technical Paper

Automated defect classification of Aluminium 5083 TIG welding using HDR camera and neural networks

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ABSTRACT

Weld defect identification represents one of the most desired goals in the field of non-destructive testing (NDT) of welds. The current study investigates a system for assessing tungsten inert gas (TIG) welding using a high dynamic range (HDR) camera with the help of artificial neural networks (ANN) for image processing. This study proposes a new dataset¹ of images of the TIG welding process in the visible spectrum with improved contrast, similar to what a welder would normally see, and a model for computing a label identifying the welding imperfection. The progress (accuracy) achieved with the new system over varying degrees of categorisation complexity is thoroughly presented.

1. Introduction

Tungsten Inert Gas (TIG) welding [1,2] is an arc welding process which is commonly employed in joining high-value precision components across a range of industries including automotive and aerospace. It was invented in the late 1930s when the requirement for joining magnesium became apparent. Since then, it has been adapted for joining steel, copper, aluminium and many other engineering alloys. It is traditionally a manually implemented process, capable of achieving higher quality weldments in comparison with other arc processes. However, it currently has many limitations, all of which are inherently related to its manual nature. It heavily relies on highly-skilled manual welders who are expensive and in very short supply. Furthermore, it lacks the flexibility to perform the welding of complex geometries and causes poor repeatability and relatively high scrap rates.

To address these limitations, the automation of TIG weld process is crucial. The monitoring and control of the weld pool during the process are critical to the automation in order to ensure quality, consistency and repeatability [3–6].

The welding process control system using some form of neural network started with the introduction of neurofuzzy architecture by Zhang and Kovacevic [7,8]. The neurofuzzy algorithm was capable of adapting and controlling the non-linear nature of TIG welding by establishing a correlation between the weld pool boundary and the top-

side and back-side bead widths.

Over the past decades, a number of sensing approaches have been proposed in the literature as a means to monitor, in real-time, the weld pool. Among these approaches are the pool oscillation method [9,10], ultrasonic testing [11–13], infrared sensing [14,15] and specular weld pool surface [16,17]. Lee et al. [18], Song et al. [19] and Lucas et al. [20] approach the concept of capturing and processing images of the weld pool. Most of these studies dedicate ample analysis for weld defects categorisation at different stages during or post-welding. The raw information for image processing and the entire approach deriving from it take two main avenues: radiographic images and visible spectrum images of welding. The two approaches have inspired each other with regards to the signal processing applied to the data, but fundamentally they approach the problem from two different points of view. While the radiography cannot monitor the weld pool, the acquisition of images in the visible spectrum has no limitation with regards to image collection. Conversely, the visible spectrum image acquisition needs to cope with the intense light emitted by the welding arc.

To illustrate this, Zou et al. [21] proposed an algorithm for real-time weld defect detection in radiographic NDT of spiral pipes. The method is based on greyscale image thresholding and application of Kalman filtering for defects tracking and false alarms exclusion. The technique provides further resilience to noise and background inhomogeneity. In another work, Boaretto et al. [22] made use of double

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¹ <https://www.kaggle.com/danielbacioiu/tig-aluminium-5083>.

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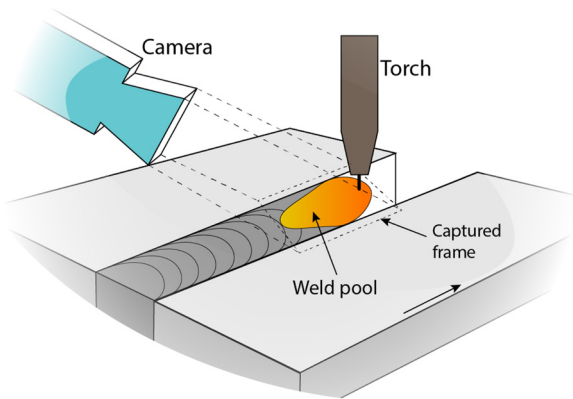


Fig. 1. TIG welding process layout.

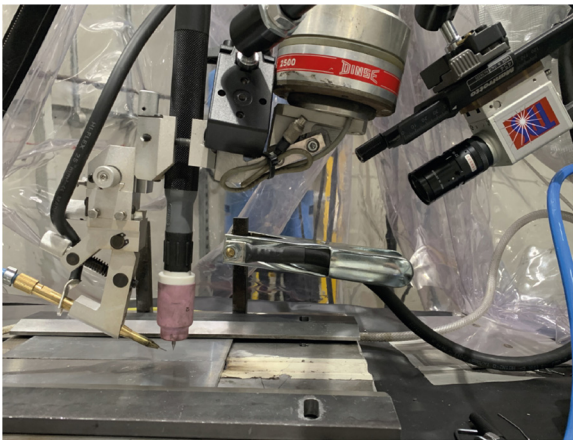


Fig. 2. Camera and robot setup.

Table 1
Aluminium 5083 composition.

Element	%
Al	Balance
Mg	4.00–4.90
Mn	0.40–1.00
Si	0.40 Typical
Zn	0.25 Typical
Ti	0.15 Typical
Fe	0.40 Typical
Cu	0.10 Typical

Table 2
Standard baseline welding parameters.

Current (A)	90
Travel speed (cm/min)	35
Voltage (V)	12
Argon flow rate (L/min)	15

wall double image (DWDI) method for capturing radiographic images. These authors subsequently located the weld bead, segmented the discontinuities and extracted the features. These features were then processed with a feed-forward multilayer perceptron (MLP) for the classification of discontinuities into ‘defect’ and ‘no-defect’. Hou et al. [23] proposed a system for identifying defects in x-ray images of welds based on Stacked Sparse Auto-Encoders (SSAE) and softmax classification. After training the system on a subset of GDXray dataset, the author achieved an accuracy of 91.84%.

On the other hand, using input that is more analogous to human

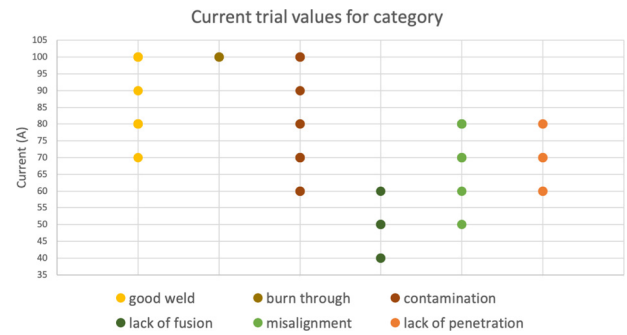


Fig. 3. Current values for each category.

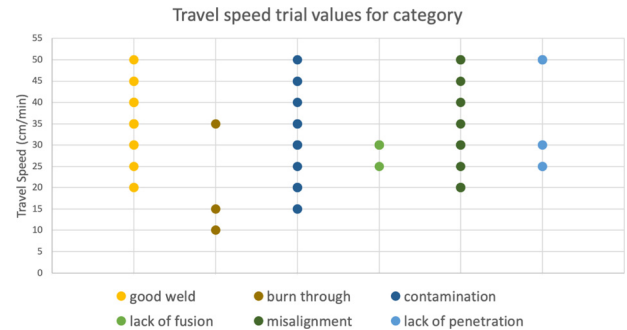


Fig. 4. Travel speed values for each category.

Table 3
Xiris XVC-1000 specifications.

Image sensor	2/3" Mono HDR CMOS
Speed/resolution	Up to 55 FPS at 1280 (H) × 1024 (V) pixels
Dynamic range	140 + dB
Bit depth	12 bits
Image data	Mono 8/16, Bayer 8/16
Shutter range	1 μs–53 s exposure

vision, Jiang et al. [24] studied the extraction of weld pool width from an image by passing it through a series of transformations: intra-group variance thresholding, fill hole treatment (advance morphological operations), FFT, edge detection (Canny), edge curve fitting and finally weld pool width extraction. Liu et al. [25] designed a procedure for capturing the top side of keyhole plasma arc welding using a CCD camera and a filter with different rates of attenuation to counter the strong arc characteristics. The authors applied the Canny filter on the image to extract weld pool edges followed by a series of custom designed and very specific steps, tailored to plasma arc welding, to reconstruct the exact weld pool boundary. In another study, Fidali et al. [26] investigated a technique which uses two cameras to acquire the visual and infrared spectrum of MAG welding process, fuse the images, then extract arc area statistics, welding area topological features and assesses intensity profile along a line in arc and welding pool areas. The authors used the multitudes of these parameters to detect different welding conditions. The end classification was carried out using k-nearest neighbour classifier achieving an accuracy around 50%.

In a suite of publications, Liu and Zhang [27–29] combined the specular weld pool surface representation of the TIG welding process with the adaptive neuro-fuzzy inference system (ANFIS) for establishing the correlation between the welding current and speed and the back-side bead width. In a subsequent study [30] the same authors attempted to fuse the human welders’ robustness to weld pool variations and the robot’s quick response capability for offsetting varying welding currents and input disturbances.

In our work, visual testing is the main focus of study, by identifying reliably and consistently defects present in weldments of aluminium

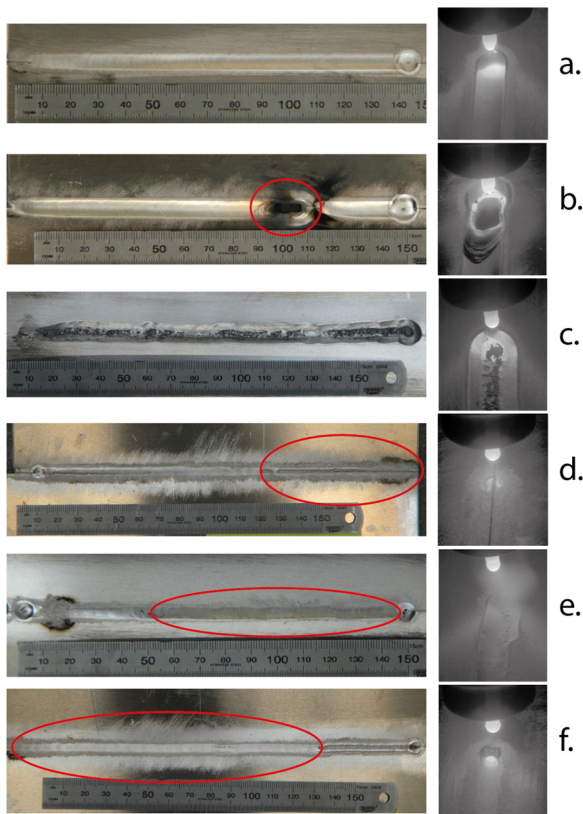


Fig. 5. Dataset samples of aluminium TIG welding. (a) good weld; (b) burn through; (c) contamination; (d) lack of fusion; (e) misalignment; (f) lack of penetration.

Table 4
Dataset split between training and test for 6-class test.

Label	Number of samples	
	Train	Test
Good weld	8758	2189
Burn through	1783	351
Contamination	6325	2078
Lack of fusion	4028	1007
Misalignment	2953	729
Lack of penetration	2819	234
Total	26,666	6588

Table 5
Dataset split between training and test for 4-class test.

Label	Number of samples	
	Train	Test
Good weld	3763	427
Burn through	1783	351
Contamination	2918	396
Lack of fusion	4182	402
Total	12,646	1576

5083 using the TIG welding process. The current study assesses the suitability of 12 neural networks (NN) architectures covering convolutional neural networks (CNN) and fully-connected neural networks (FCN) with varying internal layouts. More precisely, the principal aim of the study is to provide an alternative method for analysing images of the TIG welding process by combining the HDR camera and novel

Table 6
Dataset split between training and test for 2-class test.

Label	Number of samples	
	Train	Test
Good weld	8758	2189
Defective	17,908	4399
Total	26,666	6588

processing paradigms as neural networks.

2. Methodology

Our approach for defect identification involves utilising a camera trailing the welding process oriented directly towards the weld pool to obtain the real-time images. Fig. 1 depicts the schematic layout of the system while Fig. 2 is a real-life setup.

First, images of weld pools from “good welds” were captured and recorded then several defects were introduced and weld pools from “defective welds” were also recorded. The alteration of welding parameters, one at the time, helped with the defects introduction. For instance, a series of weld trials were performed in which the welding current was decreased in stages until “lack of penetration” was obtained. Note that all trials started with a standard “control” welding conditions given in Section 2.1.

The images captured by the camera were then categorised based on the data representative of the defects targeted in this work. Note that this categorisation ranges from the basic “good weld vs. defective weld” to more complex 6-class problem of “good weld vs. burn through vs. contamination vs. lack of fusion vs. misalignment and lack of penetration”.

2.1. Welding process

The welding process of choice in the current study is TIG welding due to the arc stability, minimal spatter and weld pool stability, used for high-quality welds, which simplifies the images analyses.

Aluminium 5083 grade was selected as the work material because it is extensively used in TIG welding. Its composition is detailed in Table 1. The plates thickness is 2 mm, and the groove angle is 90°. Table 2 lists the welding parameters used in this work as a standard “control” to achieve good welding conditions.

Figs. 3 and 4 show the distribution of the input current and the travel speed for each class examined in this study by deviating from the baseline parameters.

2.2. Camera capabilities

The camera used to record images is a Xiris XVC-1000. It uses high dynamic range (HDR) capability, of 140 + dB, to diminish the arc luminosity and bring up details from the weld pool and surrounding area, generating tones with greater accuracy. Table 3 details the camera specifications.

Fig. 5 shows the workpiece after welding with the weld appearance as recorded by the camera attached.

2.2.1. Data

The study aim is to extract information from an image representing the weld pool and surrounding area in the visible spectrum. We use a new dataset, recorded with the HDR camera, containing images with tone contrast similar to human eye vision, an example of which is given in Fig. 5, composed of 60 welding trials.

Each trial generates images at 55 frames per second, producing relatively quickly a large amount of data. The dataset contains 33,254

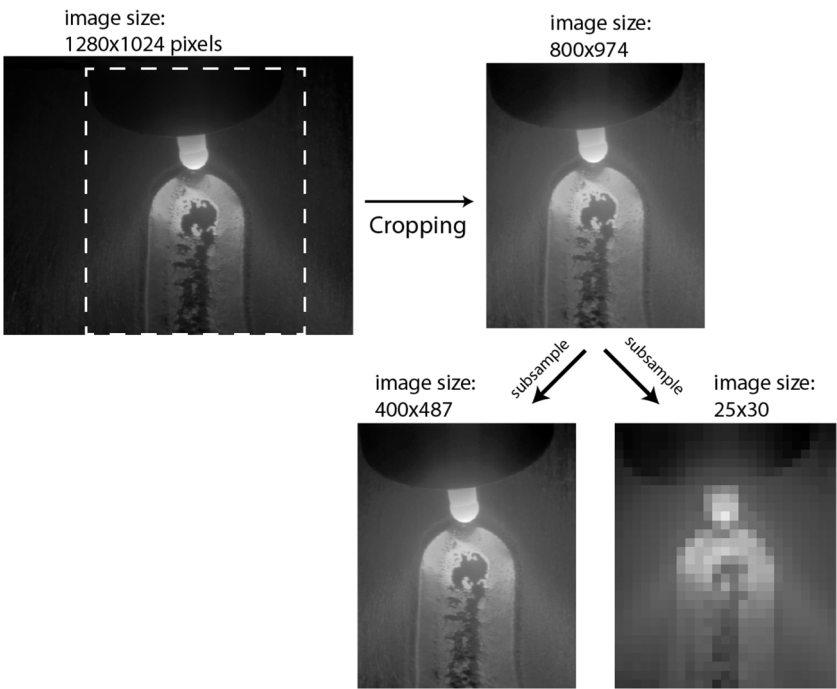


Fig. 6. Image subsampling.

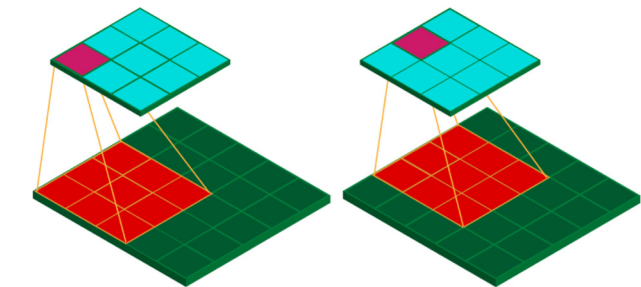


Fig. 7. Convolution between a feature map of dimension 5×5 (green) and a kernel of dimension 3×3 (red), stride 1 and image padding 0. The result is another feature map of dimension 3×3 (turquoise). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

images of TIG welding of aluminium 5083. The images were split into 6 classes, listed in Table 4, by an experienced operator.

The processing architecture requires the data to be split into two main subsets: training and testing, with approximately 75% and 25% share respectively. The data split are described in Tables 4 and 6 are for the 6-class and 2-class analysis, respectively. The exception is the 4-class analysis, described in Table 5, which uses an 88–12% split due to limitations in the generated data. The dataset for 4-class trial is a smaller version of 6-class and 2-class datasets where “misalignment” and “lack of penetration” are removed and classes with excessive number of examples reduced. The reduction excludes images from classes with excessive representation, i.e. “good weld”. As a consequence it is less representative compared to the other two. All 6-class, 4-class and 2-class analysis use the data generated within the same set of welding experiments. Table 6 “defective” category incorporates all the defects from Table 4 under one single class.

As each weld generates hundreds of images, the problem of correlation between the train and test splits became apparent. To reduce the correlation, it was ensured that no weld trial could be found in both the train and test subsets, meaning that the dataset was split based on welding trial only and not by frame setting.

Table 7
Fully connected neural network architectures.

Model reference	Number of layers	Description
7	4	downsize:[400, 487] flatten:[194,800] matmul:[194,800, 256]-relu matmul:[256, 128]-relu matmul:[128, {6, 4 or 2}]-Softmax
8	5	downsize:[400, 487] max pool:[2, 2]/2 flatten:[48,600] matmul:[48,600, 256]-relu matmul:[256, 128]-relu matmul:[128, {6, 4 or 2}]-Softmax
9	5	downsize:[400, 487] max pool:[3, 3]/3 flatten:[21,546] matmul:[21,546, 256]-relu matmul:[256, 128]-relu matmul:[128, {6, 4 or 2}]-Softmax;
10	5	downsize:[400, 487] max pool:[5, 5]/5 flatten:[7760] matmul:[7760, 256]-relu matmul:[256, 128]-relu matmul:[128, {6, 4 or 2}]-Softmax
11	5	downsize:[400, 487] max pool:[10, 10]/10 flatten:[1920] matmul:[1920, 256]-relu matmul:[256, 128]-relu matmul:[128, {6, 4 or 2}]-Softmax
12	5	downsize:[400, 487] max pool:[20, 20]/20 flatten:[480] matmul:[480, 256]-relu matmul:[256, 128]-relu matmul:[128, {6, 4 or 2}]-Softmax

Table 8
Convolutional neural network architectures.

Model reference	Number of layers	Description
1	12	downsize:[400, 487] conv:[5, 5] × [16]/1-relu, max pool:[5, 5]/3 conv:[5, 5] × [32]/1-relu, max pool:[5, 5]/3 conv:[5, 5] × [64]/1-relu, max pool:[5, 5]/3 conv:[5, 5] × [128]/1-relu, max pool:[5, 5]/3 flatten:[384] matmul:[384, 256]-relu, matmul:[256, 128]-relu matmul:[128, {6, 4 or 2}]-Softmax
2	12	downsize:[400, 487] conv:[5, 5] × [16]/1-relu, max pool:[3, 3]/2 conv:[5, 5] × [32]/1-relu, max pool:[3, 3]/2 conv:[5, 5] × [64]/1-relu, max pool:[3, 3]/2 conv:[5, 5] × [128]/1-relu, max pool:[9, 9]/9 flatten:[2560] matmul:[2560, 256]-relu, matmul:[256, 128]-relu matmul:[128, {6, 4 or 2}]-Softmax
3	10	downsize:[400, 487] conv:[5, 5] × [32]/2-relu, max pool:[3, 3]/2 conv:[5, 5] × [64]/2-relu, max pool:[3, 3]/2 conv:[5, 5] × [128]/2-relu, max pool:[3, 3]/2 conv:[3, 3] × [256]/2-relu flatten:[512] matmul:[512, 256]-relu, matmul:[256, 128]-relu matmul:[128, {6, 4 or 2}]-Softmax;
4	12	downsize:[400, 487] conv:[3, 3] × [16]/1-relu, max pool:[5, 5]/3 conv:[3, 3] × [32]/1-relu, max pool:[5, 5]/3 conv:[3, 3] × [64]/1-relu, max pool:[5, 5]/3 conv:[3, 3] × [128]/1-relu, max pool:[5, 5]/3 flatten:[1024] matmul:[1024, 256]-relu, matmul:[256, 128]-relu matmul:[128, {6, 4 or 2}]-Softmax
5	12	downsize:[400, 487] conv:[3, 3] × [16]/1-relu, max pool:[3, 3]/2 conv:[3, 3] × [32]/1-relu, max pool:[3, 3]/2 conv:[3, 3] × [64]/1-relu, max pool:[3, 3]/2 conv:[3, 3] × [128]/1-relu, max pool:[9, 9]/9 flatten:[3840] matmul:[3840, 256]-relu, matmul:[256, 128]-relu matmul:[128, {6, 4 or 2}]-Softmax
6	11	downsize:[400, 487] conv:[3, 3] × [16]/2-relu, max pool:[3, 3]/2 conv:[3, 3] × [32]/2-relu, max pool:[3, 3]/2 conv:[3, 3] × [64]/2-relu, max pool:[3, 3]/2 conv:[3, 3] × [128]/2-relu flatten:[512] matmul:[512, 256]-relu, matmul:[256, 128]-relu matmul:[128, {6, 4 or 2}]-Softmax

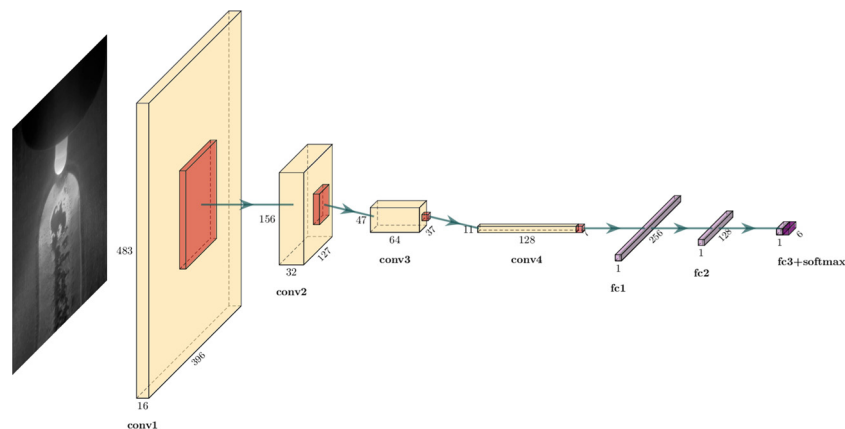


Fig. 8. An example of visualisation of feature maps dimensions for each convolution and fully connected layers for Model 1.

Table 9
Training parameters.

Learning rate	10^{-1} , 10^{-2} , 10^{-3} , 10^{-4} and 10^{-5}
Number of epochs	5
Batch size	10
First moment estimates decay rate	0.9
Second-moment estimates decay rate	0.999

Table 10
Varying parameters.

Model	12 architectures
Learning rate	10^{-1} , 10^{-2} , 10^{-3} , 10^{-4} and 10^{-5}
Classification difficulty	2-class 4-class 6-class
Input images size	400×487 px 30×25 px

Table 11
Model accuracy for the learning rate and model for 6-class classification.

Model reference	Learning rates analysed					model average (%)
	10^{-1}	10^{-2}	10^{-3}	10^{-4}	10^{-5}	
1	33.23	33.23	65.94	71.75	71.22	69.64
2	33.23	33.23	55.49	62.34	62.45	60.09
3	33.23	33.23	64.30	62.42	58.26	61.66
4	33.23	33.23	65.83	61.82	56.36	61.34
5	33.23	33.23	64.37	61.38	52.02	59.26
6	33.23	44.14	54.57	40.73	48.09	47.79
7	33.23	33.23	26.05	41.68	39.00	35.57
8	33.23	33.23	40.06	42.02	40.73	40.93
9	33.23	33.23	38.75	46.92	43.14	42.94
10	33.23	35.20	39.62	42.32	44.76	42.23
11	31.54	35.53	45.22	40.70	42.96	42.96
12	33.23	44.64	40.66	47.50	46.84	45.00
average	33.09	35.44	50.07	51.80	50.48	50.78

2.2.2. Preprocessing

The camera delivers frames of size 1280×1024 pixels, centred on the weld pool. The images contain a substantial amount of black pixels surrounding the weld pool and the welding arc as seen in Fig. 6. Therefore, the cropping reduces the original size of 1280×1024 to 800×974 . Further to cropping, the images are subsampled, reducing the size to 400×487 . The subsampling operation is necessary because of the hardware constraints during the training stage of the networks. The model receiving a higher resolution requires significantly more GPU memory.

The resolution reduction has the potential of influencing the resulting model accuracy. This study performs an ablation analysis on the

Accuracy for number of layers

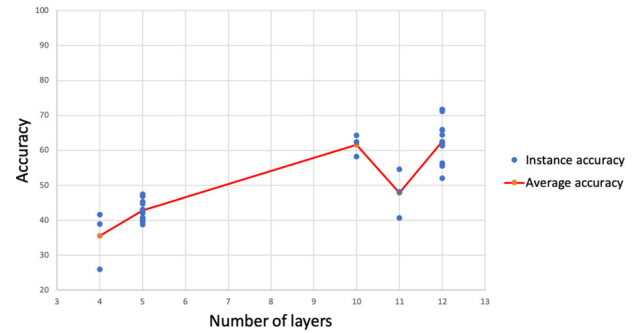


Fig. 10. Average accuracy as a function of the number of layers for 6-class classification.

Table 12
Model accuracy for the learning rate and model for 4-class classification.

Model reference	Learning rates analysed					model average (%)
	10^{-1}	10^{-2}	10^{-3}	10^{-4}	10^{-5}	
1	25.51	25.51	68.91	89.66	86.87	81.81
2	25.51	25.51	71.57	73.29	75.13	73.33
3	27.09	25.51	74.05	74.87	74.81	74.58
4	25.51	25.51	89.66	75.32	71.83	78.93
5	25.51	27.09	74.68	81.47	74.18	76.78
6	25.51	73.54	77.03	75.19	70.18	74.13
7	25.51	27.09	69.16	63.32	62.06	64.85
8	27.09	27.09	68.78	55.58	73.10	65.82
9	25.51	56.47	71.38	57.17	61.99	65.52
10	25.51	78.17	68.46	64.91	64.09	65.82
11	27.09	73.92	57.99	70.88	74.62	67.83
12	25.51	65.67	74.75	70.37	72.53	72.55
average	25.90	44.26	72.20	71.00	71.78	71.66

effect of resolution reduction on the final accuracy. The images of 400×487 pixels are subsampled to 25×30 pixels and unsampled back to 400×487 . The subsampling followed by upsampling has two reasons: it maintains the input image size of 400×487 pixels for neural networks and removes details from the baseline image of 400×487 . The result is the isolation of fidelity as the only changing parameter across comparison.

2.3. Processing architecture

The processing paradigm evaluated in the current study is based on an artificial neural network (ANN) architecture [31–33]. ANN is a lattice of computations which reduces the input dimensionality, eventually arriving at desired labels. The reason for choosing ANN rests

Models accuracy

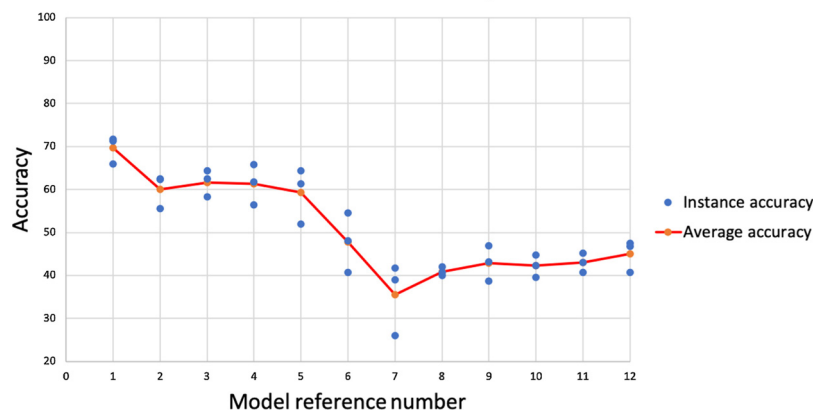


Fig. 9. Average accuracy for models trained with the learning rates 10^{-3} , 10^{-4} and 10^{-5} for 6-class classification.

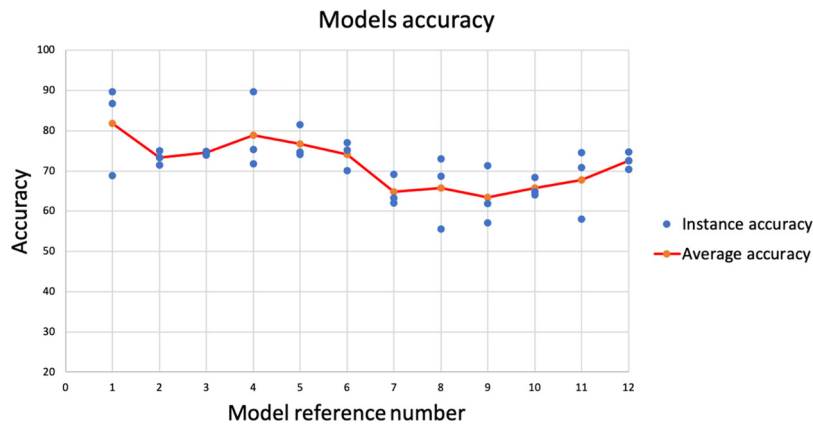


Fig. 11. Average accuracy for models trained with the learning rates 10^{-3} , 10^{-4} and 10^{-5} for 4-class classification.

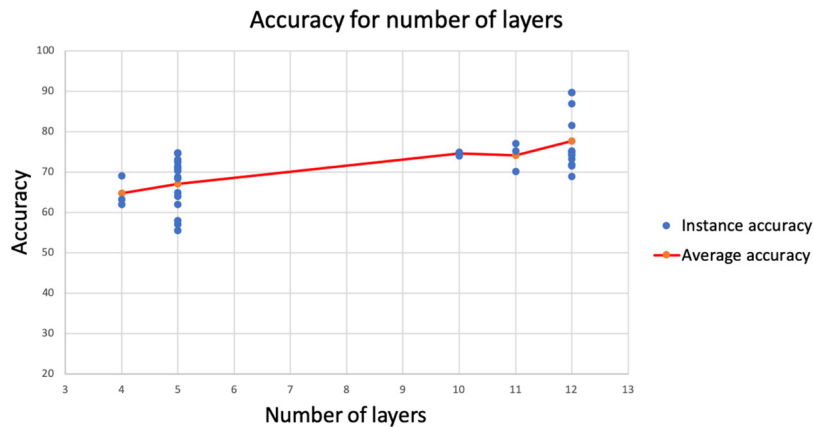


Fig. 12. Average accuracy as a function of the number of layers for 4-class classification.

Table 13

Model accuracy for the learning rate and model for 2-class classification.

Model reference	Learning rates analysed					model average (%)
	10^{-1}	10^{-2}	10^{-3}	10^{-4}	10^{-5}	
1	66.77	66.77	93.91	87.05	83.24	88.07
2	33.23	66.77	95.57	89.40	81.79	88.92
3	66.77	77.47	83.15	80.10	77.14	80.13
4	66.77	66.77	85.82	90.15	80.86	85.61
5	66.77	66.77	91.01	86.08	92.68	89.93
6	66.77	64.28	81.38	87.99	78.79	82.72
7	66.77	66.77	69.72	77.69	71.39	71.39
8	66.77	66.77	65.80	75.96	69.72	70.49
9	66.77	66.77	71.62	74.74	71.83	72.73
10	66.77	66.77	71.92	70.60	68.23	70.25
11	66.77	61.70	70.58	72.09	67.06	69.91
12	66.77	72.01	73.89	71.93	65.70	70.51
average	63.98	67.47	79.29	79.65	76.23	78.39

mostly in the processing adaptability across various lighting and appearance conditions.

The study applies the fully connected neural network architecture (FCN) [34–37] and convolutional neural network (CNN) [38] for processing the weld images. FCN and CNN are subsets of the larger ANN processing paradigm [39]. Both architectures have an input layer for receiving the image and an output layer for the classification label. In FCN there is a connection between each input pixel and every node from the subsequent layer. In case of CNN, the region for kernel application is limited to the kernel dimension. One of the first application of CNN [31] was character identification [40]. A representation of convolution dynamics is Fig. 7, where the input image (green) convolves with the kernel (red) outputting one single value (purple).

By traversing the input image one pixel at a time (stride 1) horizontally or vertically, another image (feature map) is created (turquoise). The reduction in the number of parameters required to produce the same output is significant. As an example in the current displayed setting of Fig. 7 there are $3 \times 3 = 9$ weights producing 9 outputs, while in the case of fully-connected networks (FCN), producing the same output would require $5 \times 5 \times 9 = 225$ weights because the number of parameters grows quadratically with the input image size.

The analysis in the current study covers 12 architectures, 6 CNNs and 6 FCNs. The main parameters defining the architecture variations for CNN are the convolutional kernel size, the number of kernels in each layer and stride, while for FCN the important parameters are number of layers and the number of units in each layer. Tables 7 and 8 describe in more details how layers are composed for each architecture.

The first layer, “conv:[5, 5] \times [16]/1-relu”, in model 1 in Table 8, contains 16 kernels with each kernel of dimension 5×5 , stride 1, and the rectified linear unit, ReLu [41], activation function. It produces 16 feature maps of size 396×483 each. This implies $396 \times 483 \times 16 = 3,060,288$ output values with $5 \times 5 \times 16$ (weights) + 16 (biases) = 416 parameters. For comparison purpose, the same number of outputs, with a FCN, would require $(396 \times 483 \times 16) \times (400 \times 487 + 1) = 596,147,162,688$ parameters – almost impossible to process.

Following each convolution layer, there is maximum pooling sampling layer [42]. “max pool:[5, 5]/3” translates to a kernel size 5×5 and stride 3, which samples the largest value in the receptive field.

The basic blocks in this study are the 5×5 kernels with stride 1 and 2, 3×3 kernels with stride 1 and 2, maximum pooling layers of sizes 5×5 with stride 3 and 3×3 with stride 2. The convolution and maximum pooling operators are placed at the beginning of the network

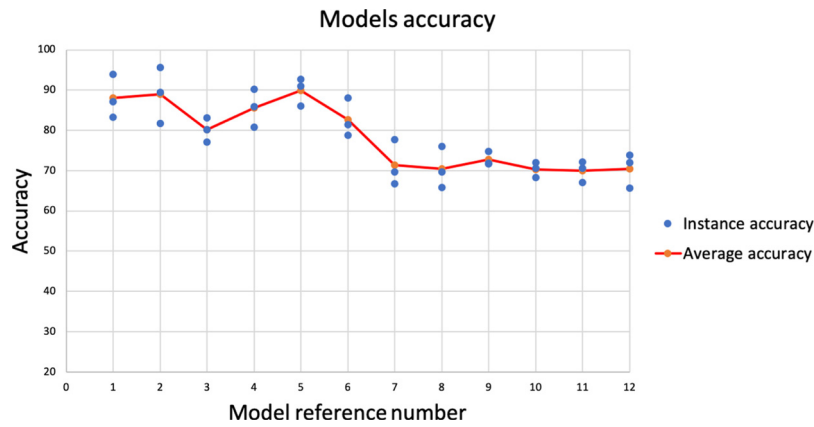


Fig. 13. Average accuracy for models trained with the learning rates 10^{-3} , 10^{-4} and 10^{-5} for 2-class classification.

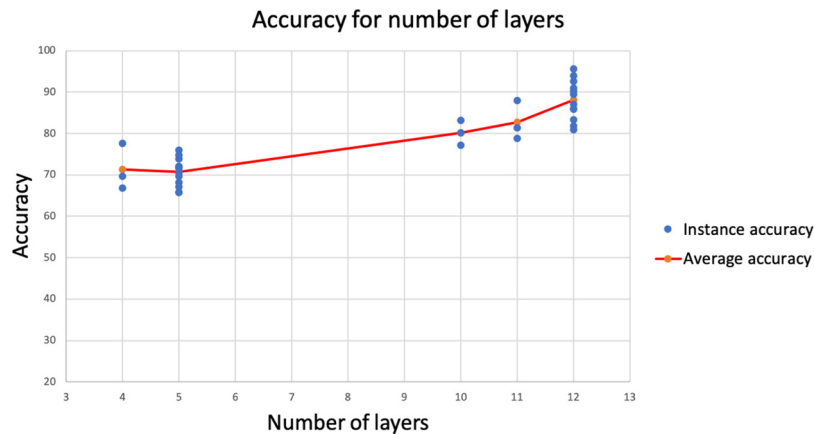


Fig. 14. Average accuracy as a function of the number of layers for 2-class classification.

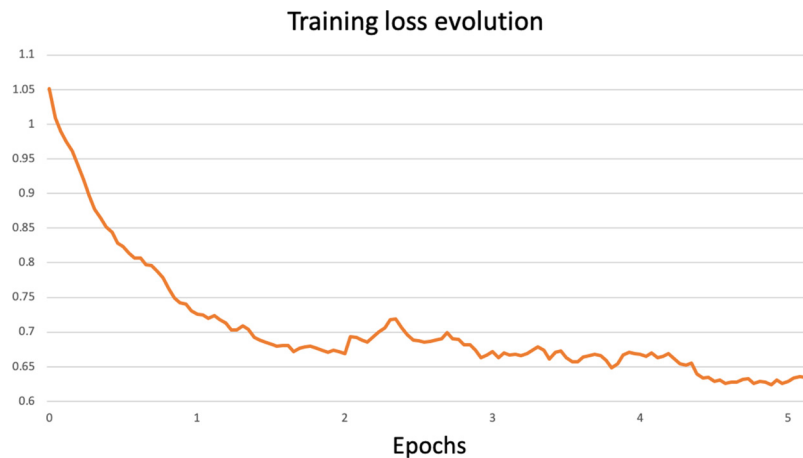


Fig. 15. Training loss evolution.

having an effect of feature reduction, minimising input from $194,800$ (multiplying 400×487) pixels to few hundreds.

After the convolution and pooling layers within each architecture, the image is flattened i.e. unrolled into a vector and denoted “flatten: [384]”, followed by fully connected layers, denoted “matmul: [384, 256]” as they are matrix multiplications.

The last two hidden layers “matmul: [384, 256]-relu” and “matmul: [256, 128]-relu” are the same for all the networks to preserve some similarity between different architectures and assess the power of representations built in previous convolutional layers.

An example of the feature maps shrinkage due to convolution and

maximum pooling is presented in Fig. 8.

2.3.1. Convergence

On top of the architecture variation, there is the process of learning, or more precisely, finding the probability distribution describing the dataset. The probability distribution is parametrised by the weights composing the kernels and fully connected layers in the architecture described in Section 2.3. The convergence algorithm used in the current study is called Adaptive Moment Estimation (Adam) [43]. The training parameters are described in Table 9

In summary, this study evaluates the neural networks accuracy on

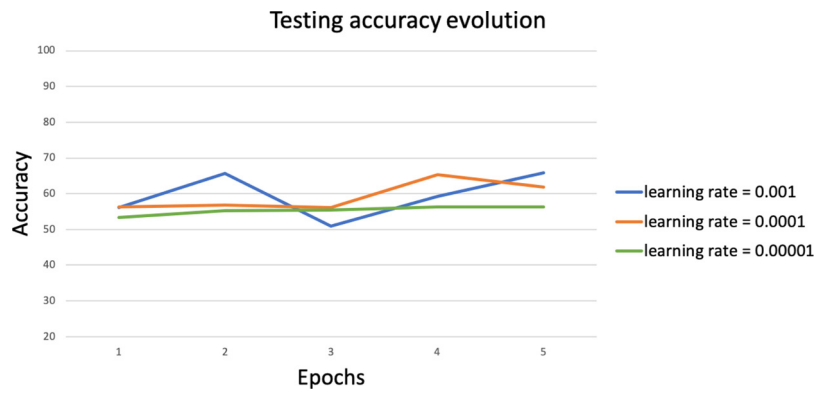


Fig. 16. Test accuracy evolution.

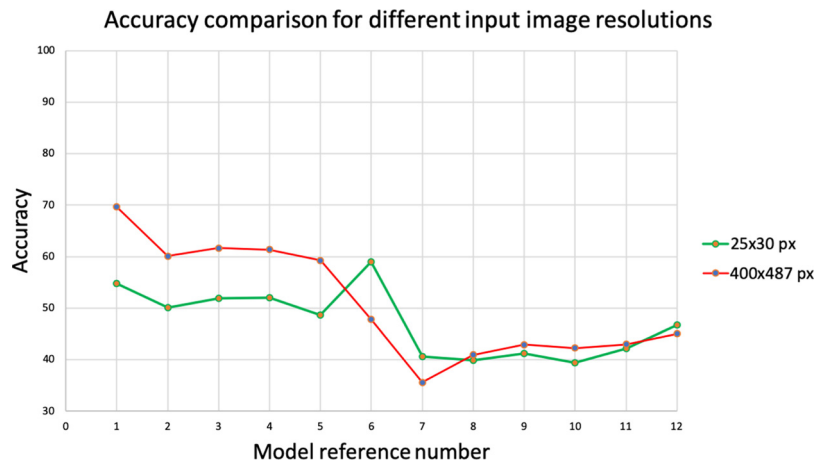


Fig. 17. Subsampling accuracy impact for 6-class defect.

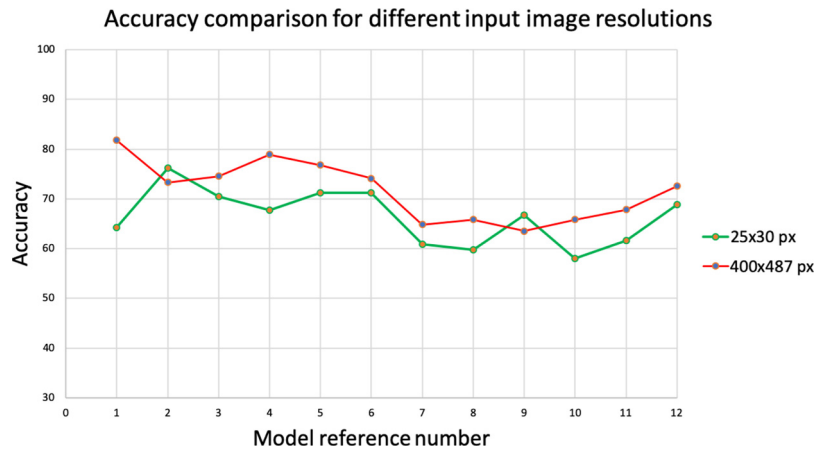


Fig. 18. Subsampling accuracy impact for 4-class defect.

classifying weld images with defects. The variable under investigation are as follows (Table 10):

3. Results and discussion

3.1. 6-class test

The most challenging test for the neural networks is the 6-class classification, for which performance over a range of architecture and learning rate variations are described in Table 11.

The architectures highlight a significant degree of performance difference between CNN and FCN. The CNN models outperform and

build better representations from HDR input images compare to FCN with a performance gap of 18% on average.

The performance numbers presented in Table 11, on the last column (dark grey background), represents the average of the three light grey columns, 10^{-3} , 10^{-4} and 10^{-5} and it measures the model's stability across a range of values for learning rate. The first two columns (10^{-1} and 10^{-2}) are omitted because the networks are not successful in representing the underlying dataset probability distribution for the learning rate chosen. 10^{-1} and 10^{-2} learning rates were too high for the architecture's internal parameters to converge to a state representative of dataset's probability distribution. In conclusion, all the learning rate greater than 10^{-2} are unsuitable for converging to an

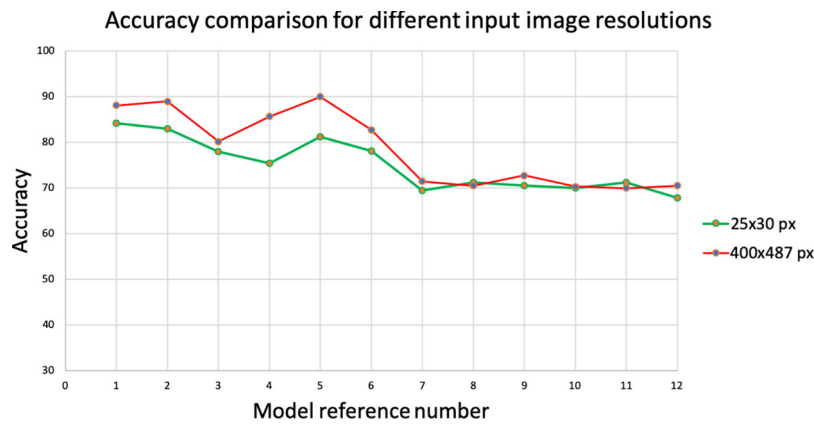


Fig. 19. Subsampling accuracy impact for 2-class defect.

acceptable solution.

Fig. 9 shows the same set of models as Table 11, displayed graphically, while Fig. 10 clusters the models based on the number of layers, highlighting the importance for increasing the networks depth.

The limit in this case is the processing power available, which for this study, was 4GB Nvidia GeForce GTX 980, able to accommodate a model of up to 12 layers. The pattern is also found in FCN, architectures with 5 hidden layers exhibiting an accuracy advantage over architectures with 4 hidden layers.

The main interest of the study is to perform hyper-parameters' (e.g. learning rate) ablation analysis on values that led to relatively successful models. A relatively successful model is one that achieves an accuracy exceeding 40% since the models tend to classify everything as the same class. In the current case that class is "good weld".

3.2. 4-class test

Table 12 shows the performance results for training the same architecture on classifying 4 types of welds.

The average performance difference between CNN and FCN shrinks to 9.5%. Figs. 11 and 12 show the average accuracy for each class and average accuracy variation for model depth increase.

The natural inclination is to set larger learning rates since the architectures are able to converge to a solution faster, requiring less training. In this regard, the FCN has a wider operating window than CNN, being able to converge even with values as high as 10^{-2} . That being said, almost all architectures examined, have peak performance in the range $10^{-3} - 10^{-5}$. Performance as a function of learning rate degrades sharply for values adjacent to 10^{-3} (namely 10^{-2}) for CNNs as well as FCN by 42% and 13%, respectively.

3.3. 2-class test

The reason almost all architectures achieve an accuracy of 67% over 2 classes in Table 13 when the random classification probability is 50% is due to a slight imbalance in test dataset (2189 good weld samples and 4399 defective). All examples are categorised as defective ($4399 / (2189 + 4399) = 0.67$), therefore no representation of data was achieved.

The results in Figs. 11 and 12 show smaller performance gap between CNN and FCN with a difference of 7.5% in favour of CNN. Analysing the samples labelled incorrectly, it is observed that most images of "contamination" are misclassified, in almost all cases, indicating the defect is not represented sufficiently well in training dataset.

The 2-class performance mirrors the pattern seen in 6-class with the exception of overall accuracy. Since only two classes are present the entire graph is shifted up reflecting simpler categorisation (see Figs. 13

and 14).

3.4. Training stability

The training duration is 5 epochs for all the neural network architectures. Fig. 15 shows the loss evolution during training stage, significant of the convergence towards a solution. In this case the loss graph represents an instance of model reference 4, but the same trend could be observed for all the models.

Fig. 16 shows the test accuracy at different points during training, notably at every epoch's end.

Figs. 15 and 16 highlight the models' rapid converge during the first epoch, while during the next 4 epochs, the models either maintain the same accuracy or at best improves it marginally.

3.5. Subsampling influence

This study analysis the impact of the resolution reduction on the final accuracy performance. The result are presented in Figs. 17–19, for the 6-class, 4-class and 2-class, respectively. Models trained using the images subsampled to 25×30 pixels then upsampled to 400×487 are compared against models trained with the images subsampled to 400×487 pixels. The fidelity reduction impacts severally the CNN architectures, particularly when the problem difficulty increases and the distinction between classes became harder, as in 6-class test. The FCNs show small decrease in accuracy performance, therefore concluding the architectures are agnostic to inaccurate pixel values and less sensitive to the gradient between pixels values.

4. Conclusion

This study investigates a system for weldment classification using a vision system composed of a HDR camera able to offset powerful arc light and capture more detailed imaging of weld pool paired with the new and adaptive classification paradigm of neural networks.

The analysis involved the construction of models based on CNN and FCN, varying internal architecture and hyper-parameters influencing the convergence of internal parameters for representing dataset's probability distribution. The models were trained using 6-class, 4-class and 2-class tests with highest accuracies of 71%, 89% and 95%, respectively. Furthermore, this study performed neural networks' robustness examination over a set of problems (6-class, 4-class and 2-class), highlighting the parameters influencing the model performance, concluding the architecture is the most important aspect given the learning rate is adequately chosen. The study also cover, the critical analysis of the errors linked to the input images fidelity reduction, highlighting the decrease in the accuracy performance.

The system required the generation of a new TIG welding dataset

representing good welds as well as different types of common defects. This study contributes with 33,254 images covering five welding defects.

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Conflicts of interest:

All authors have participated in (a) conception and design, or analysis and interpretation of the data; (b) drafting the article or revising it critically for important intellectual content; and (c) approval of the final version.

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