Appendix

1. The similarity between plasticine and metals:

For plasticine to exhibit material flow behaviour similar to metals at elevated temperatures, its nature (not the magnitude) of flow stress should be same as depicted by metals at high temperature (above recrystallization temperature and below the melting point). In metals, flow stress $\boldsymbol{\sigma}$ is a function of strain $\boldsymbol{\varepsilon}$, strain rate $\dot{\boldsymbol{\varepsilon}}$ and temperature T. Therefore, it suggests that the nature of the dependence of flow stress on strain rate and temperature should be the same as that of metal. In general, for metals, flow stress displays an increasing trend with an increase in the strain rates used in deforming the material (tested at constant temperatures). Similarly, flow stress shows a decreasing trend with the rise in temperature at which material is deformed (tested at constant strain rates). Besides, strain hardening effects become less important and are often neglected without significant loss in accuracy above the recrystallization temperature. Therefore, while deforming plasticine, variation in stress with respect to induced strain (on a stress-strain graph) should be similar to the stress-strain behaviour of metals, excluding the magnitude of stresses. These similarities can be proved through uniaxial compression tests. These tests are conducted on the plasticine at various strain rates and temperatures to determine the dependence of flow stress on strain rate and temperature. To demonstrate similarity, flow stress graphs from uniaxial compression tests are presented for strain rates of 0.0001, 0.001, 0.01, 0.1 and $1s^{-1}$ (recorded at a constant temperature of 27°C) in Figure 1(a) and at temperatures of 21, 27, 30, 33 and 35°C in Figure 1(b) (recorded at a constant strain rate of 0.001 S^{-1}). The results from the graphs confirm that plasticine complies with the flow behaviour of metals (especially many steels and aluminum alloys) at elevated temperatures. The shear friction factor for plasticine/wood combination is determined by a standard ring compression test and is found closer to 1 (sticking), which principally occurs in FSW. The similarity in thermal conditions is difficult to satisfy quantitatively. However, qualitative thermal similarity exists and is evident from Figure by the thermal softening of plasticine with increased temperatures.

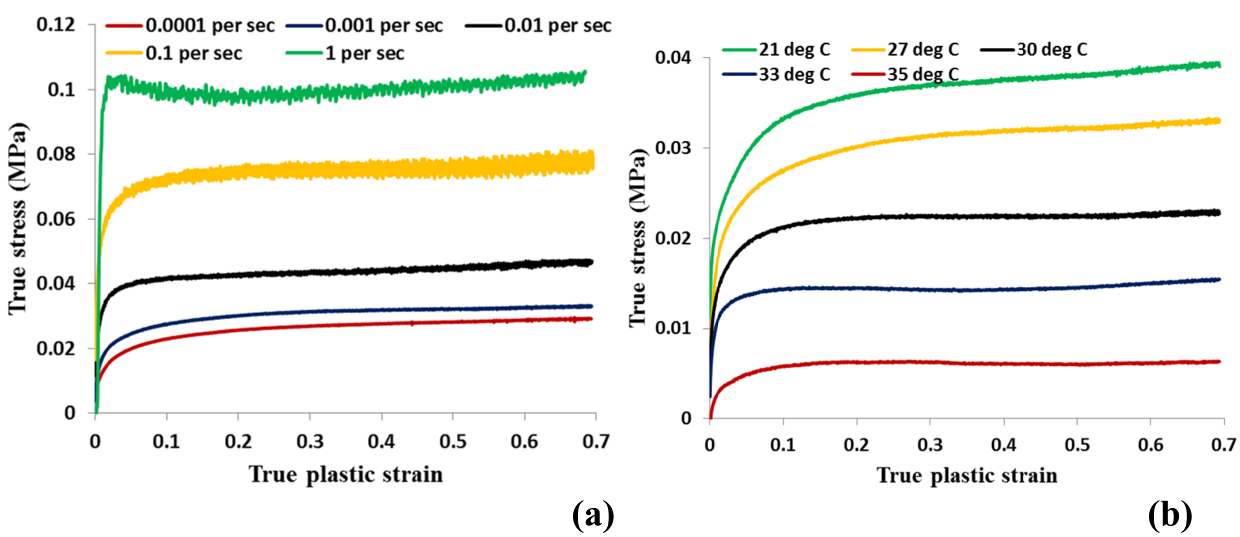


Figure 1. (a) True stress-true plastic strain curves obtained on plasticine deformed in compression at 27°C and at different strain rates. (b) True stress-true plastic strain curves obtained on plasticine deformed in compression at $0.001s^{-1}$ and at different temperatures

2. Validation of the FE Model

The accuracy of the developed model is validated with the experimentally observed temperature and average spindle torque occurring during the traverse/steady-state phase of the FSW process. The experimental temperature was recorded in the work material at a distance of 11 mm from the tool axis. The following were the process parameters in the preliminary model. Experiments and simulations were carried on the geometrically similar workpiece. Three different trials were conducted at tool rotation speeds of 400 rpm, 800 rpm and 1200 rpm, respectively. The tool was traversed at 90 mm/min with a plunge depth of 0.2 mm for each trial. Tool tilt was 2° and tool material was H13. Tool geometrical details were shoulder diameter of 20mm and tapered pin of 6/4 mm with no surface features. Work material was AA2024 of thickness 5 mm and having a density of 2780 kg/m^3, Young's modulus of 73 GPa across all temperatures and solidus temperature of 510°C (783K).

Applied boundary conditions in the FE model were:

i. Shear friction model was used with a friction factor = 1

ii. Coefficient of heat transfer between the workpiece and the tool = 11,000 W/m^2-K

iii. Coefficient of heat transfer between the workpiece and backing plate = 1000 W/m^2-K

iv. Convection coefficient = 20 W/m^2-K

v. Ambient Temperature = 20°C

vi. The fraction of mechanical energy transformed into heat = 0.9

vii. The material model used: $\overline{\boldsymbol{\sigma}} = \overline{\boldsymbol{\sigma}}(\overline{\boldsymbol{\varepsilon}}, \overline{\dot{\boldsymbol{\varepsilon}}}, T)$

i.e., flow stress is a function of strain, strain rate and temperature

The temperature was recorded with a k-type thermocouple at a similar location in the FE model as in experiments. Tool torque from simulations was compared with spindle torque from the FSW machine. Figure 2(c) shows the trends for temperature (max value at the designated location during tool traverse) and spindle torque (average value during traverse/steady-state phase) at three different tool rotation speeds, i.e., 400 rpm, 800 rpm and 1200 rpm. The data from simulations are in good agreement with experimental values and capture similar trends as reported by other researchers (*Ref. 34, 40 and 41 in the Manuscript*). The validated model is extended for commercially pure aluminum by incorporating work material properties like flow stress data, melting point, etc.

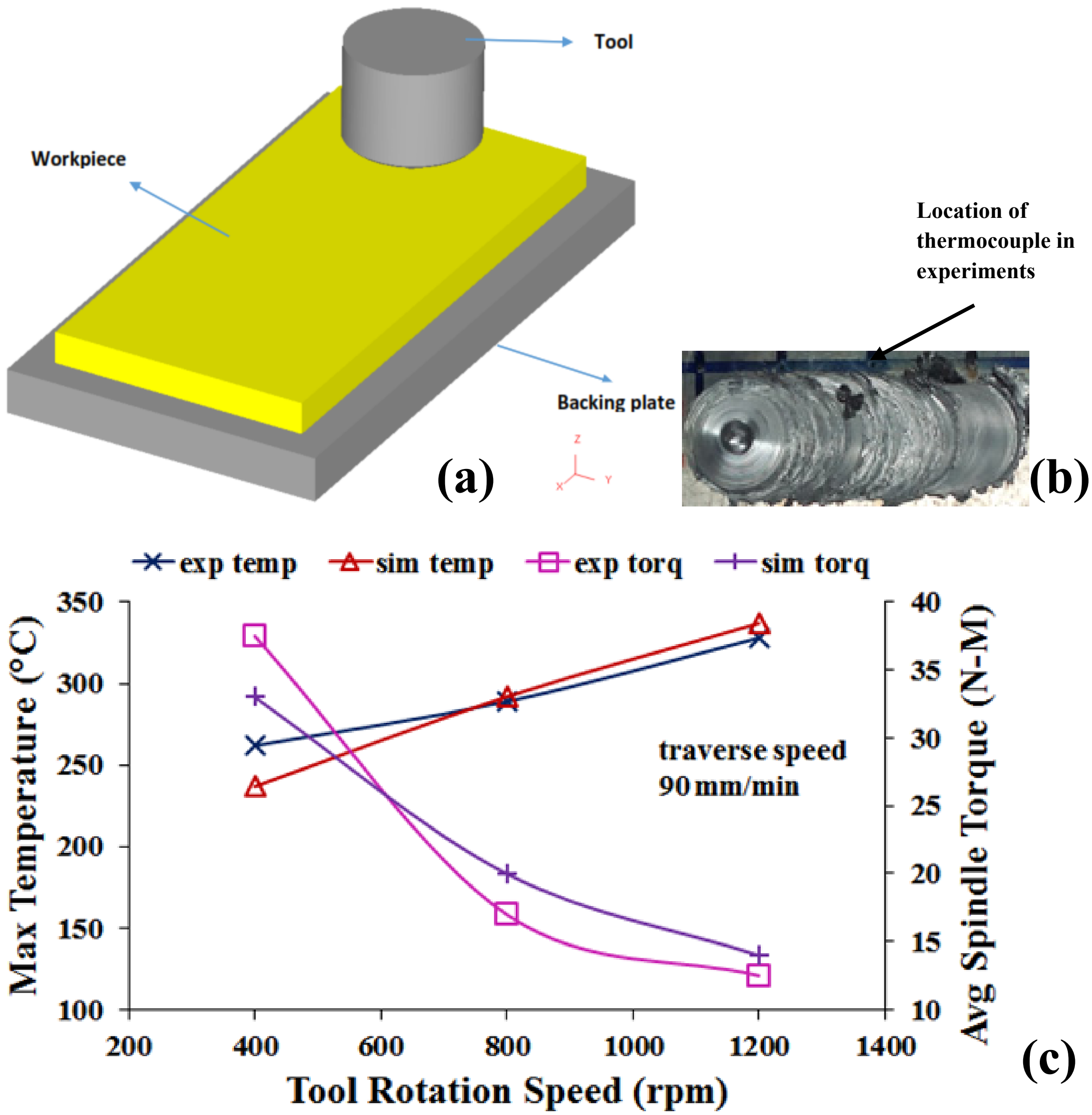
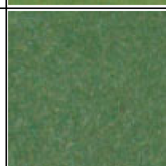
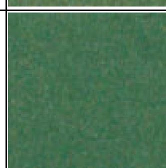
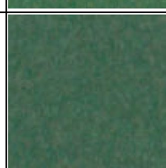
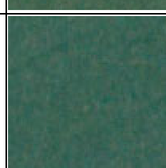
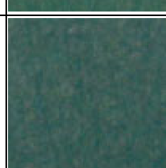
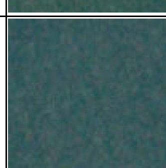
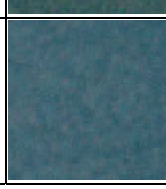


Figure 2. (a) FE model in DEFORM 3D (b) Photograph from experiments showing thermocouple location (c) Estimated and experimental values with trends for maximum temperature and average spindle torque for validation

3. The extent of mixing and its quantification

To check the extent of green generated blue and yellow plasticine is hand-mixed (mechanically mixed) in different proportions, as shown in Table 1. Blue plasticine is added in steps of 5 gms to yellow plasticine to attain a percentage value in steps of 10. The total sample weight is 50 gms. It results in a total of 11 samples with first as yellow and last as blue. The intermediate samples are a mixture of blue and yellow, which generate different shades of green post mixing. All the samples are hand mixed in a similar way for a constant time duration of 10 minutes. The time period is finalized after observing no further change in the produced secondary colour following that period. Smooth cuts were obtained on samples by slicing with thin copper wire. This step is crucial for obtaining good quality macrographs. The same method is used for slicing plasticine welds. Photographs of the sliced samples are captured in identical conditions used for plasticine welds. Nikon D40 DSLR camera is used for photography and all images are taken with the same camera settings and similar lighting conditions.

Table 1. HSV values with mean and standard deviation for generated shades of secondary colour

% of blue in yellow	**Colour**	**H_{mean} (°)**	**H_{sd}**	**S_{mean} (%)**	**S_{sd}**	**V_{mean} (%)**	**V_{sd}**
0b 100y		48.7	0.8	75.4	3.0	93.2	1.4
10b		90.8	2.9	44.8	2.2	55.2	1.2
20b		110.8	6.5	32.3	2.8	46.7	2.1
30b		136.2	4.7	38.9	4.3	44.0	1.7
40b		143.1	4.6	34.0	4.2	39.7	1.5
50b		158.5	3.9	40.2	4.7	39.0	1.4
60b		168.8	4.5	35.4	5.5	36.6	1.9
70b		183.0	4.8	37.3	5.7	36.0	1.5
80b		196.0	3.1	42.4	4.5	44.2	1.6

90b		206.9	3.3	44.2	4.9	45.3	1.9
100b 0y		213.3	0.8	60.2	5.2	55.5	1.8

A portion of 100 x 100 pixels is cut (without resizing camera images) from digital images of sliced specimens. These are shown in Table 1. RGB values of the images are read from MATLAB and converted to values of HSV colour space. Since data varies from pixel to pixel over a range, mean and standard deviation are computed for Hue (H), Saturation (S) and Value (V) and summarized in Table . Hue, saturation and value components for all the 11 images (corresponding to mixtures of respective proportions of yellow and blue plasticine) are plotted to identify their trends. As expected, the hue follows an ascending trend (reasonably linear) with respect to incremental mixtures of blue in yellow, as shown in Figure 3. It is due to different shades of green generated between yellow and blue plasticine for different proportions of mixing. It can be noticed that all the colours are differentiable visually and follow a colour trend, i.e., from yellow-yellowish green-dark green-bluish green-blue. Samples from 10b to 50b exhibit clear green shade with increasing intensity. Samples 60b and 70b are bluish-green, whereas 80b and 90b are bluish. Similarly, 10b exhibits yellowish green.

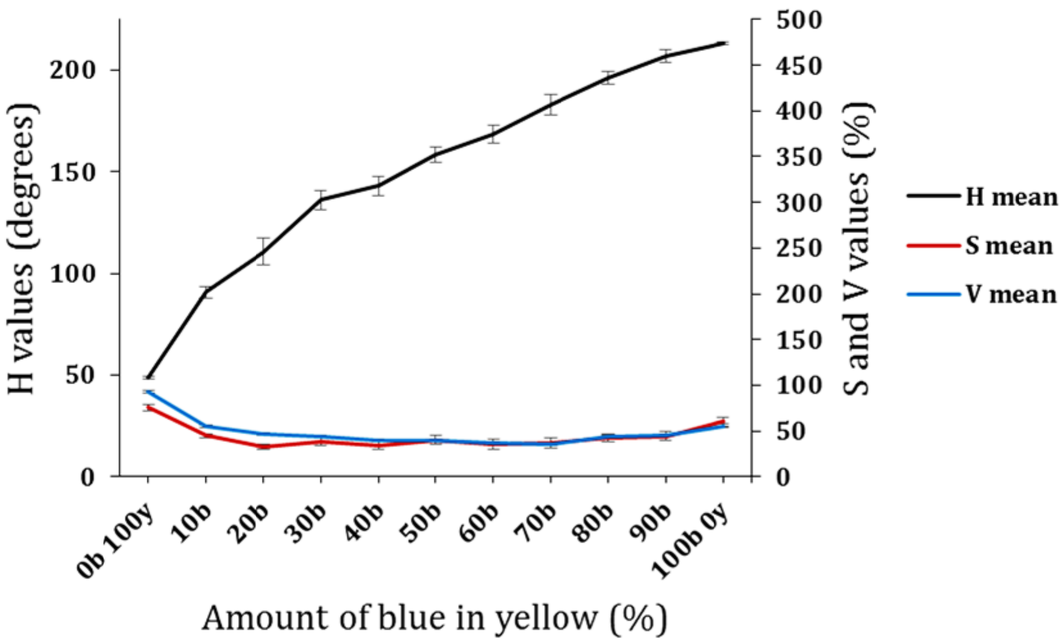
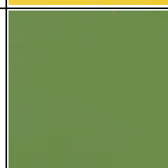
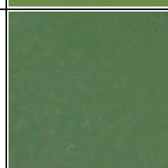
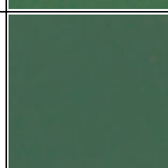
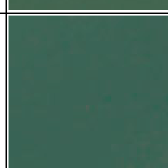
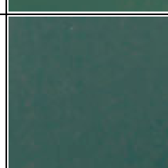
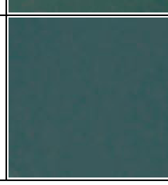
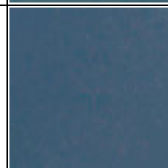


Figure 3. Trends of H, S and V values with respect to generated colours between yellow and blue

This indicates that the hue component is a better measure to trace the degree of mixing. However, tracing can be further refined by reducing the standard deviation (reducing the relative spread of data). The spread is due to white pixels (glister at points in the image), possibly due to excessive illumination of oily areas during photography with flash. This can be termed as noise and can be reduced by filtering. The bilateral filter is used for image denoising. Another advantage of it is, it performs the task without disturbing the visual structures (preserves object contours), unlike Gaussian convolution. Adobe Photoshop provides a fast and simple bilateral filter variant under the name "surface blur." Table 1 is further refined by applying the bilateral filter and represented as Table 2. Figure 4 shows the corresponding graph.

Table 2. HSV values with mean and corresponding standard deviation after application of the bilateral filter to secondary colours produced for different blends of blue and yellow

% of blue in yellow	**Colour**	**H_{mean} (°)**	**H_{sd}**	**S_{mean} (%)**	**S_{sd}**	**V_{mean} (%)**	**V_{sd}**
0b 100y		48.8	0.4	75.6	1.1	93.2	0.6
10b		90.3	0.5	44.7	0.7	55.1	0.3
20b		109.1	1.3	32.3	1.0	46.6	0.4
30b		135.5	1.2	39.1	0.7	44.0	0.4
40b		142.4	1.0	33.9	0.9	39.7	0.3
50b		158.5	1.5	40.1	1.6	39.0	0.3
60b		169.3	1.3	35.4	2.1	36.6	0.9
70b		182.9	0.9	37.6	1.5	35.9	0.3

80b		195.7	0.7	42.1	1.9	44.1	0.6
90b		206.7	1.0	44.1	1.8	45.3	0.6
100b 0y		213.5	0.4	60.3	0.9	55.9	0.4

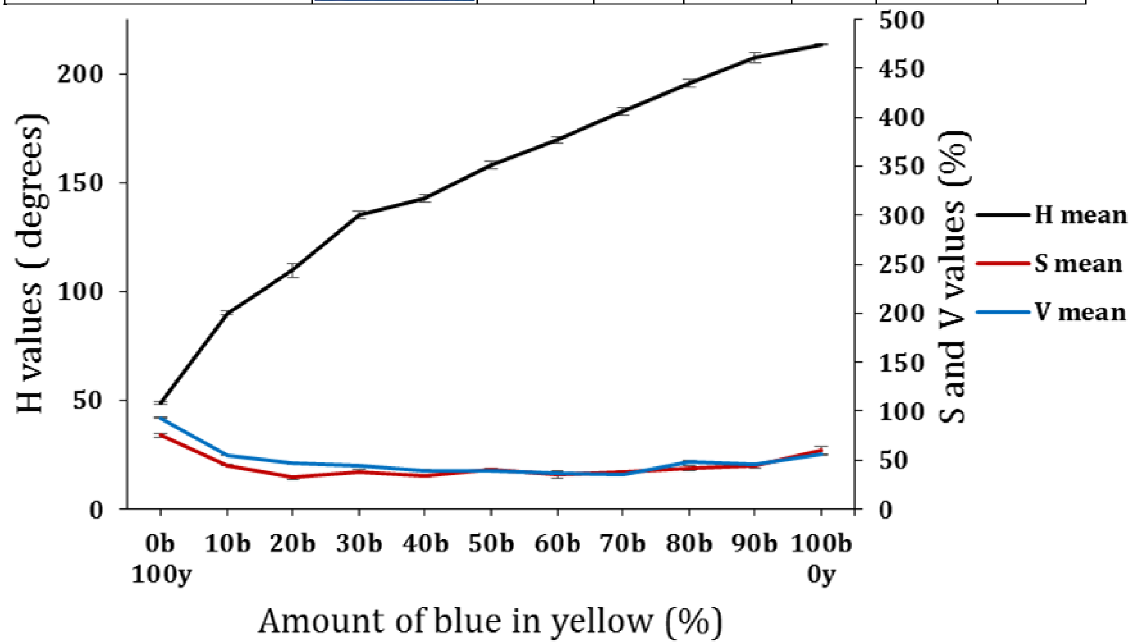


Figure 4. Trends for the values of H, S and V as a function of colours produced for different blends of blue and yellow. Bilateral filter used for noise reduction. The standard deviation drops accordingly

Further studies are carried referring to hue element in Table 2. The filter is applied to images of interest (weld cross-sections obtained under different welding conditions) where an attempt is made to quantify mixing. The green area fraction in the weld region is determined using the ImageJ image processing tool. The analysis is made for the area covered by a specific type of green in the weld region. It is done by using the threshold option for the targeted range of Hue component in HSB colour space. Similar weld areas are maintained for all the analysis by carefully cropping the weld region to a fixed pixel size of 300 in height and 800 in width. To compensate for any variations probably due to repetitive use of plasticine and lighting effects, a 3% error range is added to the hue element from Table 2. Table 3 is made after including this compensation.

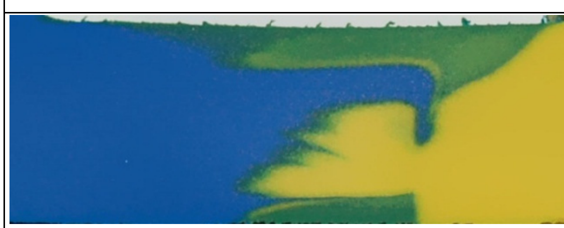
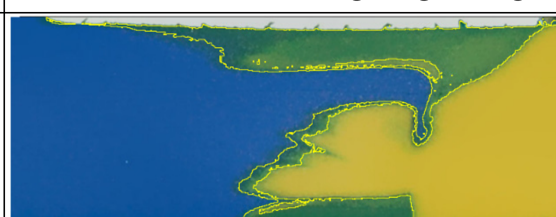
Table 3. Hue values after accommodating compensation expressed in respective scales

% of blue in yellow	0b 100y	10b	20b	30b	40b	50b	60b	70b	80b	90b	100b 0y

H_{mean} (°)	48.8	90.3	109.1	135.5	142.4	158.5	169.3	182.9	195.7	206.7	213.5
H_{mean} (on the scale with 255 units)	34.6	63.9	77.2	96.0	100.9	112.3	119.9	129.5	138.6	146.4	151.2
With a 3% error range (°)	47.3 - 50.3	87.6 - 93.0	105.8 - 112.3	131.4 - 39.6	138.1 - 146.7	153.7 - 163.3	164.2 - 174.4	177.4 - 188.4	189.9 - 201.6	200.5 - 212.9	207.1 - 219.9
With a 3% error range (on the scale with 255 units)	33.5 - 35.6	33.5 - 35.6	74.9 - 79.5	93.0 - 98.9	97.8 - 103.9	108.9 - 115.7	116.3 - 123.5	125.6 - 133.4	134.5 - 142.8	142.0 - 150.8	146.7 - 155.7

A mixture of 20b to 70b is considered for initial studies. Weld samples made under different tooling conditions are analyzed for hue spanning between 105° to 189°. Further, as per the need, analysis can be carried for specific ranges of H_{mean}. In ImageJ, the hue is expressed on the scale varying between 0 to 255 units. Therefore, scale in degrees is converted to ImageJ units by multiplying it with a conversion factor of 0.7083. Table 4 shows a cross-sectional weld sample 800 pixels wide and 300 pixels in height, amounting to a total weld area of 240000 pixels. Targeted area (for green ranging from 105° to 189°) is selected and highlighted by the yellow boundary. It amounts to an area with 41300 pixels. The area fraction of the specified green in the weld region is 0.1721.

Table 4. Example of weld sample before and after selection of the targeted green region

Weld before selection	**Weld after selection of the targeted green region**
	
Total weld area 240000 pixels (800 pixels in width and 400 pixels in height)	41300 pixels of the green area selected (green ranging from 105° to 189°, equivalent to 74.4 to 133.9 on a scale with 255 units)

It is clear from these examinations that the Hue attribute of colour is suitable for tracking the degree of mixing in the proposed solution as it follows the linearly ascending trend with an incremental increase in the proportion of blue in yellow. Hue component is obtained from digital images of weld cross-section by converting their RGB colour maps to HSV colour maps. The proposed method gives scope to conduct specific analysis (Quantification) with respect to particular mixtures and their distribution across the weld cross-section.