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# Water jet incremental sheet metal forming: a critical state-of-the-art review and a proposal for technological windows

Mathieu Miroir, Romain Laniel, A. Brient, Olivier Kerbrat

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## Article Title:

Water jet incremental sheet metal forming: a critical state-of-the-art review and a proposal for technological windows

## Name, contact details and affiliations of all authors

No.	Name(s) of Author(s)	Highest academic degree	Author Affiliations	Email address / Telephone number	Postal Address	ORCID
1	Mathieu MIROIR	Dr.	Univ Rennes, CNRS IPR, UMR 6251, F-35000 Rennes, France	<a href="mailto:mathieu.miroir@univ-rennes1.fr">mathieu.miroir@univ-rennes1.fr</a> / +33 (0)2 23 23 54 40	IPR, Camus de Beaulieu, Bat 10B, 35042 Rennes Cedex France	0000-0001-5884-6103
2	Romain LANIEL	Dr.	Univ Rennes, CNRS IPR, UMR 6251, F-35000 Rennes, France	<a href="mailto:romain.laniel@univ-rennes1.fr">romain.laniel@univ-rennes1.fr</a> / +33 (0)2 23 23 40 88	IPR, Camus de Beaulieu, Bat 10B, 35042 Rennes Cedex France	0000-0001-6732-0904
3	Antoine BRIENT	Dr.	Univ Rennes, CNRS IPR, UMR 6251, F-35000 Rennes, France	<a href="mailto:antoine.brient@univ-rennes1.fr">antoine.brient@univ-rennes1.fr</a> / +33 (0)2 23 23 41 06	IPR, Camus de Beaulieu, Bat 10B, 35042 Rennes Cedex France	
4	Olivier KERBRAT ( <i>corresponding author</i> )	Dr	CNRS GeM, UMR 6183, Univ Rennes, F-35000 Rennes, France	<a href="mailto:Olivier.kerbrat@ens-rennes.fr">Olivier.kerbrat@ens-rennes.fr</a> / +33 (0)2 99 05 52 75	ENS Rennes, Campus de Ker Lann, 35170 Bruz, France	0000-0001-8365-5480

## ABSTRACT

Nowadays the development of innovative processes is a major challenge for industries which want to prototype functional workpieces. Incremental Sheet Forming (ISF) is a good alternative for sheet metal prototyping to ensure flexibility, accuracy of the part produced and cost effectiveness. A derived process, the Water Jet Incremental Sheet Forming (WJISF), has been undergoing development since 2001 and this paper purpose to give its state of the art. Different eclectic industrial fields could be concerned by WJISF process: automotive, micro-electronics, medical and aerospace industry for example. As the ISF process, the WJISF device needs a multi-axial machine, but it also needs a pressure pump with a sufficient flow rate and pressure. In an environmental point of view, this process can be seen as a “green” one giving that the water can be recycled and there is no lubricant.

A general methodology has been defined to rigorously investigate this process and focus on researchers’ teams, technological feasibility, numerical simulations, machine-tool uses and real parts manufacturing. The study presented here provides summarizing evidence, especially technological windows, which give quick view of the actual knowledges and will help scientists and industrials to find WJISF parameters related to their needs. A lot of simple tests have been carried out with numerical and experimental comparisons. Nevertheless, few real parts have been manufactured and the complex shape obtained by WJISF remains a scientific field to explore.

## KEYWORDS

Sheet metal forming; Water jetting; Dieless manufacturing; Literature review; Technological window

## 1. INTRODUCTION

In manufacturing today, prototyping functional workpieces is a major challenge that can lead to the development of innovative processes. The three major issues for prototyping processes are flexibility, accuracy of the part produced, and cost effectiveness. For sheet metal prototyping, incremental sheet forming (ISF) is a good alternative to stamping. This dieless manufacturing process provides great flexibility and allows a variety of geometries to be achieved.

From a green manufacturing point of view, ISF could be improved, as it still needs a lubricant to reduce friction between the workpiece and the tool. This friction would otherwise lead to tool wear and a poor surface finish. Using a water jet (WJ) instead of the forming tool could be a relevant alternative.

The water jet incremental sheet forming (WJISF) process has been undergoing development since 2001, and the present paper focuses on these past 20 years of scientific research. We defined a general methodology for investigating this innovative prototyping process, as manufacturers who are interested in it need to know the general state of the art. More specifically, we collected data on materials, machines, and parameters, and sought to identify the main scientific deliverables, namely approaches, workpieces, and forming limits. We also set about identifying the future scientific problems of this green prototyping forming process to optimize it.

## 2. GENERAL CONTEXT: INCREMENTAL FORMING OF SHEET METAL PARTS USING A WATER JET

Sheet metal forming achieved using the stamping method requires forming tools with complex shapes. In a prototyping context, these tools take too long and are too expensive to make for stamping to be considered a relevant solution. ISF has proved to be a good solution, as it allows the metal sheet to be shaped by means of a simple geometry-based forming tool. The material is plastically deformed at the contact point of the forming tool. A variety of 3D shapes can be obtained, depending on the tool path.

ISF has two main drawbacks, starting with accuracy. Although ISF can be achieved using a computer numerical controlled (CNC) machine, improving precision can require more specific parts, such as a supporting die or even a specific machine and tools, in the case of two-point ISF, where two moving tools are used to achieve the local deformation. A second drawback is tool wear. The process principle involves friction between the tool and the workpiece. Although this friction can be reduced by using lubricant or a rotating tool, tool wear remains a major concern that can reduce the quality of the surface finish.

Using a WJ as a forming tool could be a relevant alternative, as it would address the tool wear issue. With ISF, the main tool is a rod-shaped punch with a smooth hemispherical head, whereas with WJISF,

the main tool is a high-velocity WJ, as shown in Figure 1. The WJ is created by a high-pressure pump and expelled through a canon. The high-speed fluid tool is controlled by two parameters: pump pressure  $p_w$  and canon diameter  $d$ . There is an initial gap  $h$  between the canon end and the metal sheet of thickness  $t_0$ . The latter is held by blank holders and is deformed layer by layer by means of a multi-axis trajectory, with numerically controlled displacements and velocities.

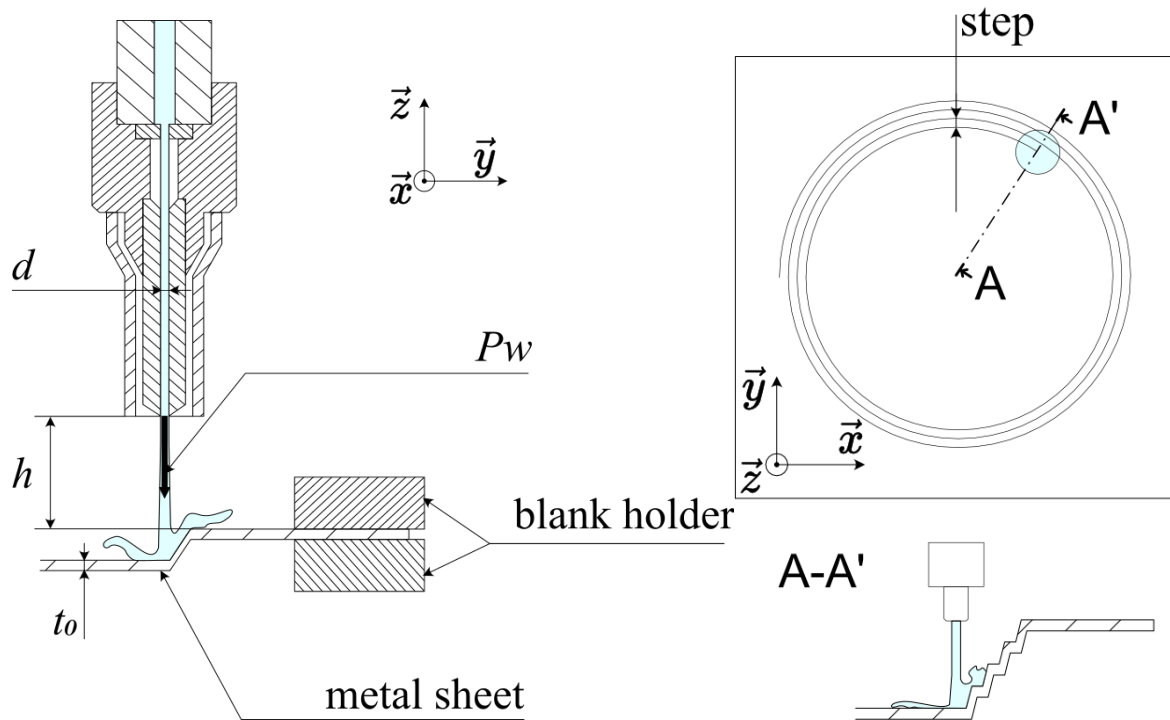


Figure 1. Water jet forming principle

This specific process is derived from the WJ cutting process, which uses a combination of water and abrasive particles to remove material from the workpiece. In WJISF, the abrasive is omitted, so that the metal sheet is deformed without any damage.

Given the potential benefits of using a WJ instead of a rigid tool for ISF, several researchers have worked on the process and reported the theoretical background, experiments, and numerical simulations. However, no overview has been undertaken to understand exactly what is technologically feasible. From an industrial point of view, the two major questions are which types of machine tools could be dedicated to the process, and which parts could be produced. To identify the main parameters that must be considered when forming a metal sheet using a WJ, technological windows

must be created to indicate the range of parameter values, based on experimental and numerical tests. As numerical simulation can help to accurately predict the behavior of a metal sheet under different manufacturing parameters, it is important to fully explore the theoretical background and model the process.

The objective of the present study was thus to provide a comprehensive description of the state of the art of WJISF. Based on the typology of reviews analyzed by [1], we adopted a critical review methodology. Our aim was to present, analyze and summarize all the literature on WJISF that was published between 2000 and 2020. The methodology, inspired by [2], is shown in Figure 2.

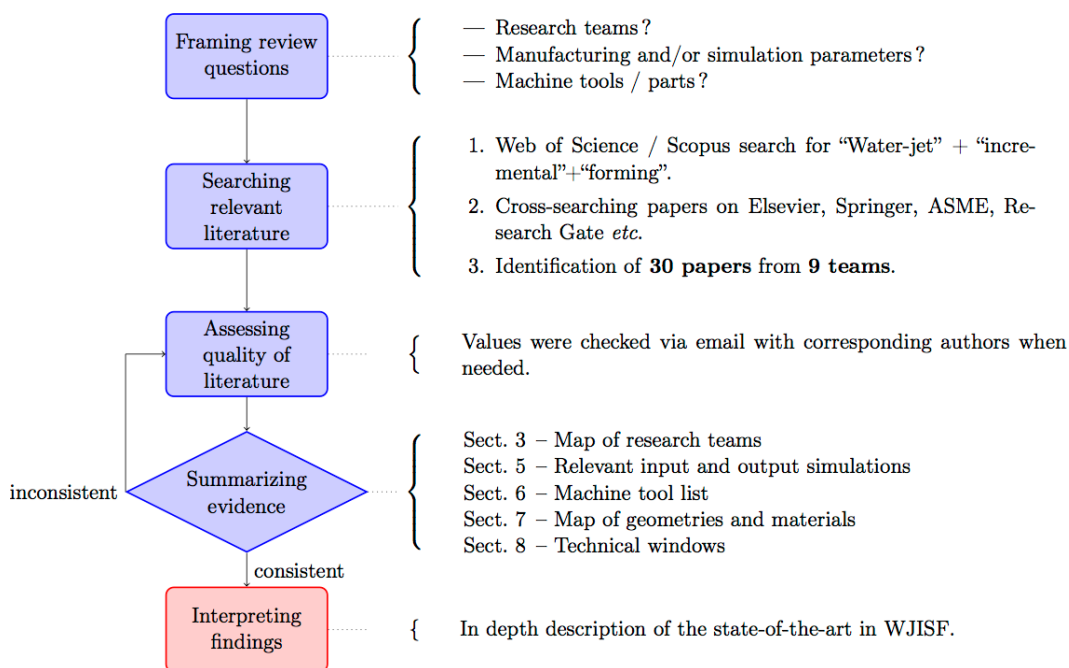


Figure 2. Methodology for analyzing an innovating process (here, WJISF), from the review questions to the in-depth description. Application to the WJISF

In this critical review, the first stage was to frame the relevant questions. Five questions fell within the ambit of this review:

- Question 1, concerning *researchers*: Which research teams have worked on the process?
- Question 2, concerning *technological feasibility*: What are the manufacturing parameters that make it possible to form a sheet metal part using this process?

- Question 3, concerning *numerical simulation*: What are the numerical parameters that can efficiently simulate the process?
- Question 4, concerning *machine tools*: Which machine tools are adapted to the process?
- Question 5, concerning *parts*: Which kinds of parts should be manufactured using this process?

The second stage was to find the relevant literature via scientific databases. Scopus yielded 39 papers, and Web of Science 29 papers, when we applied the search terms “water-jet” AND “incremental” AND “forming”. These papers were then either viewed on the publishers’ websites (Elsevier, Springer and ASME for conference proceedings) or directly read in open-access publications. Other relevant papers were gleaned from the authors’ webpages (ResearchGate, Google Scholar or institutional pages). The references of each paper were then checked to find the corresponding articles. The outcome was an exhaustive list of 30 papers.

The third stage was to assess the quality of the literature. We carefully analyzed papers from journals with high impact factors, papers presented at national or international conferences, and papers available in open-access publications. The sole inclusion criterion was that the topic of the paper should be WJISF. In some cases, we emailed the corresponding authors asking them to provide more precise information or data. The caliber of their responses reflected the authors’ keen interest in this process.

The fourth stage involved summarizing the evidence to answer each of the five questions:

- 1) *Researchers*: a map of different research teams, organized by country of institution, showed the number of publications and the years of publication, and a table listed all the authors and their affiliations, together with the titles of the papers and other publications
- 2) *Technological feasibility*: the in-depth analysis of the different manufacturing parameters used in the experimental studies allowed us to generate technological windows.
- 3) *Numerical simulation*: we drew up a list of models, elements and parameters that had been used in different numerical simulations.

4) *Machine tools*: the machine tools that had been used to produce experimental parts were analyzed, and a table listed their main characteristics.




5) *Parts*: we produced a map of the real parts that had been produced with WJISF, to help readers understand which geometries and which materials might be concerned by future industrial applications.

If needed, in the case of inconsistent values, we asked authors to go through our review and check and/or correct data.

The fifth stage involved interpreting the findings and providing an in-depth description of WJISF.

### 3. RELEVANT LITERATURE

As shown in Table 1 and Figure 3, we analyzed 30 papers. These were divided into nine teams and four main domains: theoretical analysis, numerical simulation, experiments, and real-world part manufacturing. Many papers, of course, fell into more than one domain.

Team / Countries	Affiliations	Ref.	(T)	(S)	(E)	(R)
<b>T1</b> 	<b>Tokyo Institute of Technology</b>	Iseki 2001 [3]				
		Iseki 2007 [4]				
<b>T2</b> 	<b>University of Ljubljana</b>	Jurisevic 2006 [5]				
		Jurisevic 2006 [6]				
		Jurisevic 2008 [7]				
		Petek 2009 [8]				
		Sajn 2011 [9]				
<b>T3</b> 	<b>Corus Research, Development &amp; Technology</b>	Emmens 2006 [10]				
		Emmens 2007 [11]				











<b>T4</b> 	<b>Ningbo University of Technology</b>	Cheng 2010 [12]				
		Cheng 2011 [13]				
<b>T5</b>   	<b>Northwestern University, Shanghai</b> <b>Jiao Tong University,</b> <b>University of Nottingham,</b> <b>University of Sheffield</b>	Lu 2011 [14]				
		Lu 2017 [15]				
		Lu 2018 [16]				
		Shi 2019 [17]				
		Shi 2019 [18]				
<b>T6</b> 	<b>Shenzhen Institutes of Advanced Technology,</b> <b>Chinese University of Hong Kong,</b> <b>Harbin Institute of Technology,</b> <b>Shenzhen</b> <b>College of Advanced Technology,</b> <b>Tonglin University,</b> <b>Yantai Vocational College</b>	Mao 2011 [19]				
		He 2011 [20]				
		Luo 2012 [21]				
		He 2013 [22]				
		Li, H. 2013 [23]				
		Li, J. 2014 [24]				
		Li, H. 2014 [25]				
		Wei 2015 [26]				
<b>T7</b> 	<b>Shenyang Aerospace University</b>	Zhang, L. 2013 [27]				
		Zhang, L. 2013 [28]				
		Zhang, L. 2015 [29]				
<b>T8</b> 	<b>Xi'an Jiaotong University</b>	Zhang, Q. 2015 [30]				
		Zhang, Q. 2016 [31]				
<b>T9</b> 	<b>Islamic Azad University</b>	Teymoori 2016 [32]				

Table 1. Full list of authors, affiliations, and papers divided into nine teams (T1 T9) and four domains (theoretical analysis (T), numerical simulation (S), experiments (E), and real-world part manufacturing (R))

The first ever study was published in 1999 by Hideo Iseki, from Team 1 (Tokyo Institute of Technology), in *Transactions of the Japan Society of Mechanical Engineers* (not reported in this study because

available only in Japanese). The first English version was published in *JSME International Journal, series C: Mechanical Systems, Machine Elements and Manufacturing* in 2001 [3]. In 2007, Iseki published another article [4] reporting experiments using a WJ and shot to form shells from a stainless-steel sheet.

Another pioneer in WJISF was Team 2 from the University of Ljubljana, Slovenia (Bostjan Jurisevic, Viktor Sajn, Mihael Junkar, Franc Kosel, Karl Kuzman, and Ales Petek). This team published five papers in 2006-2011 and produced the first technological windows [5-9].

W.C. Emmens, from Team 3 (Corus RD&T), mainly worked on the application of WJISF for steel beverage can deformation, publishing two papers in 2006 and 2007 [10] [11].

In 2010, XiaoMin Cheng, Lin Zhou and colleagues from Team 4 (Ningbo University of Technology in China) published a paper on the simulation of a circular truncated cone [12], followed in 2011 by a paper describing the making of different shapes using an experimental device [13].

Team 5 is still active in this field. It brings together different researchers around Jian Cao (Department of Mechanical Engineering, Northwestern University), including Bin Lu, H. Long, M. W. Mohamed Bazeer, S. Ai, J. Chen, and H. Ou in 2011-2017, and Yi Shi, Kornel F. Ehmann, and Weizhao Zhang since 2018. They have carried out numerical and experimental comparisons of WJISF with or without die [14-18]. They have developed their own machines to carry out their experiments.

The scientists in Team 6 came from six Chinese universities, and spent 5 years working on a project to form sheet metal using a high-pressure WJ. Their approach was quite comprehensive and started quite conventionally with several theoretical and numerical studies during the early years [19-21], followed by experimental studies [22] [24], including real-world part production [23] [25] [26].

Ling Yun Zhang and associates in Team 7 (Shenyang Aerospace University) worked on WJISF simulations of copper alloys for 3 years. They essentially proposed simplified modelling [27-29].

In 2015-2016, scientists in Team 8 (Xi'an Jiaotong University) borrowed a numerical approach from liquid jet generation and applied it to metal sheet deformation [31]. The main originality of their work was to use oil instead of water for power delivery [30].

In 2016, F. Teymoori and associates in Team 9 (Islamic Azad University) published a single, but wide-ranging paper on WJISF [32], encompassing both theoretical and experimental domains.

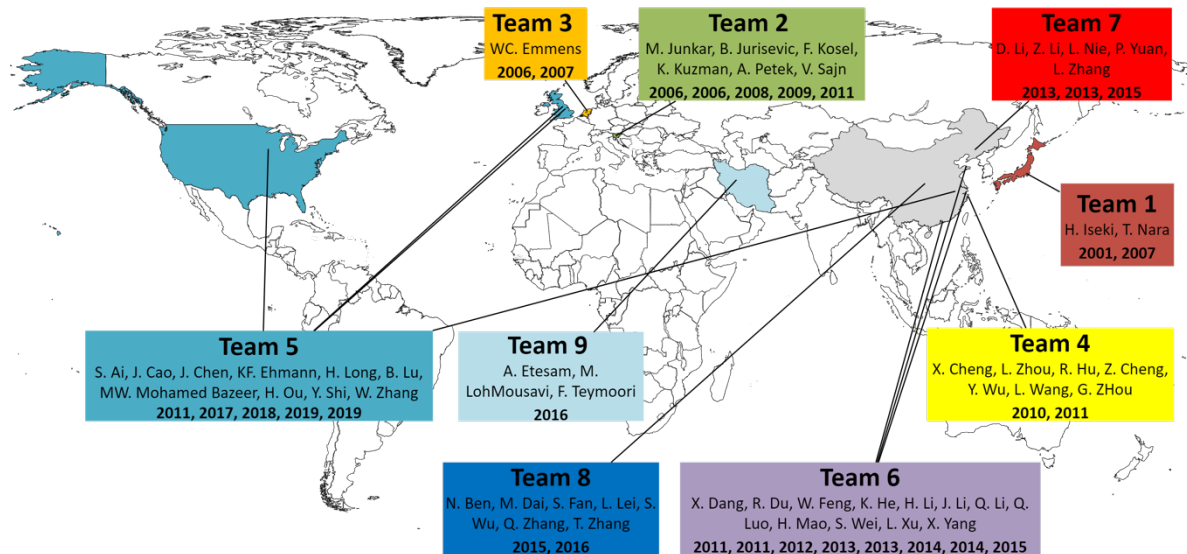


Figure 3. Map of the WJISF research teams (numbered in chronological order), with publication years in bold

## 4. THEORETICAL ANALYSIS

The first approach to understanding the process is to provide sufficient theoretical background concerning WJ use. The following section therefore explains the theoretical models that were used by the different teams.

Starting in 2001, Iseki (Team 1) innovatively proposed substituting the rigid forming tool with a high-speed WJ. He conducted experiments and provided an approximate calculation method for bulge height and strain distributions (uniform logarithmic strain, width strain, thickness strain) [3]. The theory was based on a plane-strain deformation model, membrane theory, and the momentum theory of hydrodynamics. Iseki assumed that the predictions for the shell of a quadrangular pyramid frustum

and a circular cone frustum were generally in good agreement with experimental values obtained for an annealed aluminum sheet.

A theoretical model of an axis-symmetrical, incompressible, turbulent free-surface flow was developed by Team 2 [6] [9]. This was used to simulate the impact of a WJ on the impingement rigid surface. Measuring surface pressure distribution at the interface between the WJ and the impingement rigid surface experimentally validated the finite-element analysis (FEA) simulation. Calculated pressure distributions across the surface were in good agreement with those obtained experimentally. The main outcome of this contribution was the FEA simulation and numerical validation of a high-velocity WJ impinging on a flat rigid surface at an impact angle of  $90^\circ$ , which shed light on the influence of process parameters such as water pressure  $p_w$  and WJ nozzle diameter  $d$  on the WJISF process.

An analytical model was developed by Team 5 to evaluate the size effect in the WJISF process. The Figure 4 shows that the model is built with respect to key parameters including sheet thickness, part dimension, jet size, jet pressure, and distance from blank holders [14]. An analytical equation based on the Von Mises criteria allowed the team to evaluate minimum forming pressure and forming resolution.

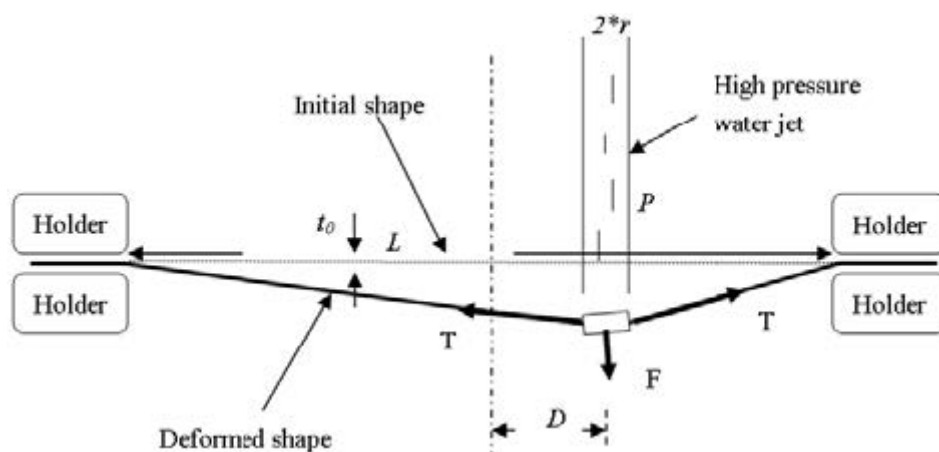


Figure 4. Input parameters of a theoretical model [14]

Team 6 published two theoretical contributions. First, they studied the deformation of sheet metal under WJ impact loading by both theoretical analysis and experimental method [19]. The distribution of axial dynamic WJ pressure and the impact pressure on a sheet metal surface were subjected to theoretical analysis. The theory and the method described in this paper provided a basis for the further study of WJISF. The team then introduced truncated cone part forming based on WJISF, describing its theoretical model and experimental validation [24]. The theoretical model they developed was based on plane strain assumption and work-energy theorem. It mainly revealed the relationships between the key process parameters (especially WJ pressure) and truncated cone parts forming an angle, which is very useful for predicting the forming angle according to WJ pressure or determining WJ pressure for different cone angle parts. To validate the theoretical model, they then manufactured a truncated cone workpiece on a homemade WJISF machine. Results showed that the theoretical shape closely matched the experimental one.

Finally, Team 9 used a coupled Eulerian–Lagrangian approach to simulate the whole WJISF deformation process of a conical part using the three-dimensional FEA method [32]. The Eulerian elements were used to model the WJ, and the Lagrangian elements to simulate the sheet and tools. The geometry of the workpiece, thickness distribution, and surface pressure distribution, volume fraction of water in the Eulerian elements, and vectors of the WJ flow were studied using the FEA method. In addition, the relationship between bulging height, pump pressure and inclination angle of a deformed conical copper part by WJISF was approximated using an analytical method proposed by other researchers, with a plane-strain formulation and the momentum theory of hydrodynamics. To verify the accuracy of their calculations, the team experimented with the WJISF of an annealed copper sheet. The numerical and analytical results were generally close to the experimental ones. In addition, most of the thinning was found to occur in the early stage of WJISF and close to the first path of the defined WJ trajectory. Surface pressure was higher at the stagnation point but was lower than the water pressure before injection from the WJ nozzle.

These theoretical contributions followed two main steps: WJ impact models, then metal sheet deformation models. In the first step, authors described WJ behavior by referring to hydrodynamic theory, to give WJ pressure distribution relative to process parameters. In the second step, they predicted the final shape and forming limits of the metal sheet, based on mechanical theory and simplification assumptions. Many papers also reported numerical simulations.

## 5. SIMULATION

Many of these theoretical approaches were implemented in software to numerically simulate the process. The main aim of these simulations was to predict what could be obtained in terms of deformation, displacement, strain, and stress of the forming sheet, without conducting expensive and time-consuming experiments with real-world parts. The chief difficulty in simulating WJ forming is that the traditional FEA for modelling the sheet cannot be adapted for modelling the WJ. Therefore, computational fluid dynamics (CFD) has been used by many authors, resulting in a combination of FEA and CFD analysis.

Team 2 started to define the WJISF domain by means of technological windows based on water pressure and stand-off distance [6]. The main tool (high-velocity WJ) was analyzed using a 2D finite element model, with a mixed non-stationary turbulent fluid flow and standard  $k-\epsilon$  turbulence behavior. The interaction between the WJ and a rigid flat surface was simulated, and the surface pressure distribution observed. The numerical results closely matched those that had been obtained experimentally, even if the FEA simulation was conducted in two dimensions. In another paper, this team provided the technological window for WJISF and characterized the attributes of the WJ used as the main tool [9]. An FEA simulation of axis-symmetrical, incompressible, turbulent free-surface flow was developed to simulate the impact of a WJ on the impingement rigid surface. The calculated pressure distributions along the surface were compared with those obtained experimentally. The area of the metal sheet affected by WJ pressure was found to be significantly greater than the WJ cross-section. The basic problem in numerical simulations is numerical pressure instabilities around the

stagnation point, at the interface between the WJ and the impingement rigid surface. To reduce these instabilities, a huge number of finite elements must be generated close to the stagnation point.

Team 4 introduced a shell mesh FEA simulation and experimental comparison of circular truncated cone forming using a WJ and a shore [12]. The numerical model used a shell mesh in Ansys software and included four assumptions: the plate had to be uniform, isotropic, and the volume could not change at any time; the material in deformation areas was treated as plane deformation; the WJ was regarded as a rigid body during the forming; and the friction between the WJ and workpiece had to be ignored. After modelling and simulating the forming process, the simulated displacement was found to be very close to the experimental one. The authors concluded that the adoption of model, initial parameters, boundary condition, constraint, and so on, in the simulation was basically reasonable and should be considered as a reference method for simulating other parts before processing.

Team 5 published four numerical papers within a decade. In [14], comparisons were made between WJISF (with or without supporting die) and a conventional ISF process with a rigid tool based on FEA simulations. A plane-strain model was implemented in Abaqus, and an in-house subroutine controlled WJ contact pressure. Results suggested that the dimensional accuracy of WJISF can be controlled by a supporting back plate, and WJISF yields a better distribution of strain and thickness reduction than ISF does. [16] [17] experimentally studied the influence of four key process parameters (WJ pressure, incremental step/pitch, feed rate, and relative WJ diameter) on the geometry of a truncated cone shape and corresponding surface quality. A numerical model was developed to predict the shape of the truncated cone part after WJIMF (microforming) with given input process parameters. Results proved that the formed part's geometric properties predicted by the numerical model were extremely close to the measured ones. The team's last paper reported a systematic experimental and numerical Abaqus study of WJIMF with three supporting dies [18]. The influence of process parameters and tool path on the geometry of the formed part was significant for WJIMF with supporting dies. This study

proved that the geometric accuracy of the part is improved by using supporting dies, as opposed to dieless WJISF.

Team 6 studied sheet metal deformation under WJ impact loading by mean of both a theoretical analysis and an experimental method [19]. FEA simulations were carried out to predict the sheet metal plastic deformation under different parameters, including WJ pressure, nozzle diameter, and sheet metal thickness, according to the distribution of impact pressure. Simulations showed that plastic deformation depth increased as WJ pressure and nozzle diameter increased, or as sheet metal thickness decreased. The authors also sought to predict the whole deformation process through multistep simulations [20]. A fluid structure interaction simulation for WJISF was performed using a CFD approach. The relationships between workpiece material deformation and nozzle diameter, and between deformation and water pressure were then calculated. Finally, the fluid structure interaction simulation model was simplified to the structure simulation model, by adopting the SHELL181 element and using a pressure that acted directly on the workpiece, instead of the CFD model. Their final paper described a numerical simulation approach to analyzing high-velocity WJ characteristics and impact pressure [21]. For the complexity of WJ formation in air, they used a multiphase mixture flow model, and the simulation was performed with Fluent software. The simulation included the hydrodynamic characteristics and pressure distribution of high-velocity WJ in air. The decay of pressure at different distances along the centerline under different pump pressures was analyzed and the length of the initial region of the WJ was determined. In addition, the impact pressure of the WJ at different stand-off distances was simulated. This paper provided theoretical parameters for WJISF.

Team 7 was one of the few to provide numerical data for copper alloy WJISF. [28] reported an FEA simulation of the WJ forming method. An experimental versus simulation comparison was carried out on a copper alloy channeling test. The model simulation was simplified in a reasonable mechanical way. By changing the displacement condition, this model could simulate the forming process with different tool paths. [27] focused on the distance from the square processing trajectory to the center,



and the effect of water pressure on the limits of forming height. The authors ran an FEA simulation of high-pressure WJ box-shape piece incremental forming. Based on this result, they put forward a new method whereby layers are formed with different water pressures to improve WJISF accuracy. This method was shown to be feasible by FEA simulation. A comparison of springback between high-pressure WJ forming and stamp forming was then carried out, using Abaqus software [29]. There was less springback with high-pressure WJ forming than with stamp forming, and WJ pressure has no impact on springback for small-curvature workpieces. By contrast, the greater the interlayer distance, the greater the springback.

Team 8 innovated by using oil as the forming liquid instead of water [30]. The authors carried out theoretical analysis and numerical simulation with Fluent software to measure the influence of jet nozzle geometry on jetting pressure and velocity, showing that the best conical angle of the nozzle was 13°. Simulation results indicated that the preferable jetting distance was 15-30 mm, and the dynamic pressure distribution approximately obeyed a Gaussian distribution on the cross-section of the oil jet. Aluminum sheets with a thickness of 0.3 mm were used in the local bulging experiment and simulation to investigate the process parameters of high-pressure oil jet forming. The dynamic effect of jetting pressure was studied using Abaqus/Explicit. Results showed that the deformation of the aluminum sheet increased as oil pressure increased. This team also studied copper alloy WJISF. In [31], the CFD software Fluent was used to simulate WJ generation in the WJ nozzle impacting on a rigid surface. Results showed that stagnation pressure decreased with jetting distance, owing to the momentum exchange and turbulent diffusion between the WJ and the air. The researchers ran both an experiment and a simulation of local bulging of 50- $\mu\text{m}$ -thick copper foil. The Figure 5 gives some results of this Abaqus model. The differences between the simulated results and the experimental values were below 10%. An experiment and a simulation for microstretching 30- $\mu\text{m}$  thick copper foil were conducted to form a cylinder part.

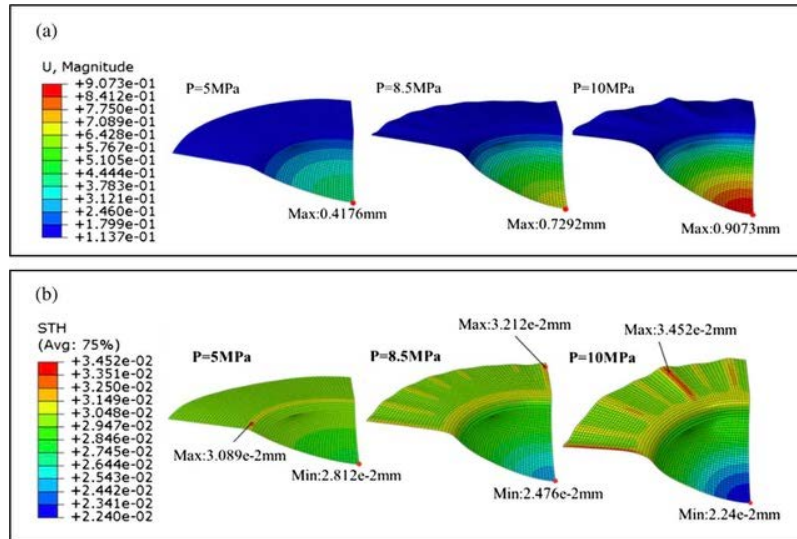


Figure 5. Simulation displacement (a) and thickness (b) distributions [31]

Team 9 adopted a coupled Eulerian–Lagrangian approach to simulate the whole deformation process of WJISF of a conical part [32]. A three-dimensional finite element model predicted the geometry of the workpiece, thickness distribution, and surface pressure distribution. Results showed that the numerical and analytical results were generally close to the experimental ones. Surface pressure was found to be higher at the stagnation point, lower than the water pressure before injection from the WJ nozzle.

All these studies yielded numerical results that are summarized in Table 2. Most of these were checked experimentally, as described in the following section.

Team / Ref.	Model	Process	Material	Input varying parameters	Output controlled parameters
T2	[6] 2D FEM of fluid (mixed fluid behavior)	WJ impact	Rigid surface	Stand-off distance [15-45] mm	Pressure distribution
	[9] 2D FEM of fluid (axis-symmetric)	WJ impact	Rigid surface	Pressure [6-12] MPa	Pressure distribution Velocity Stagnation point instability

<b>T4</b>	[12]	2D FEM (shell mesh + plane strain-) with ANSYS	WJISF: truncated cone	Metal	Fixed values	Displacement
<b>T5</b>	[14]	2D FEM (explicit, plane strain-) with Abaqus & home pressure routine	Comparison WJISF, WJISF + die, ISF: truncated cone	Al 1050, Inox 304, Ti6Al4V	Fixed values	Displacement Strain Thickness
	[16,17]	FEM (explicit, dynamic) with Abaqus & VDLoss pressure	Micro WJISF: truncated cone	Stainless steel	Pressure Incremental step Feed rate Relative water jet diameter	Displacement Roughness
	[18]	FEM (explicit, dynamic) with Abaqus & VDLoss pressure	Micro WJISF + die: truncated cone	Stainless steel	Fixed values	Displacement Roughness
<b>T6</b>	[19]	2D FEM (181 shell mesh + plane strain-)	WJ impact	Steel 204, Al 6061-T4	Pressure [20-100] MPa Canon diameter [1.7-2.1] mm Thickness [0.4-0.8] mm	Impact depth
	[20]	Mixed CFD (fluid) & FEM (workpiece)	WJ impact and WJISF: truncated cone	Q235	Pressure [20-70] MPa Canon diameter [1-4] mm	Displacement Impact depth
	[21]	Multiphase flow model with Fluent	WJ impact	Rigid surface	Stand-off distance [30-100] mm	Pressure distribution
<b>T7</b>	[28]	2D FEM (S4R shell mesh)	WJISF: channel	Copper alloy	Fixed values	Displacement
	[27]	FEM with Abaqus	WJISF: truncated cone	Copper T2	Pressure [35-60] MPa Incremental step	Displacement Formability
	[29]	FEM with Abaqus	Comparison Stamp, WJISF + die: curves	2Al2-0	Pressure [35-60] MPa Incremental step [2-4] mm	Displacement Springback

T8	[30]	Fluid (Fluent) + 2D & 3D FEM (Abaqus) + Gaussian pressure distribution	Oil-WJISF: channel	Al. LF21	Pressure [8-20] MPa Stand-off distance [15-30] mm Conical angle	Displacement
	[31]	Mixed CFD (Fluent) & FEM explicit & implicit (Abaqus, mesh 624 CAX4R)	Micro WJISF + die: truncated cone	Copper foil	Pressure [2-10] MPa Stand-off distance (optimum 40 mm)	Displacement Stagnation pressure
T9	[32]	Mixed Lagrangian & Eulerian FEM (shell mesh + plane strain)	WJISF: truncated cone	Cu ETP	Stand-off distance	Displacement Thickness Pressure distribution Stagnation pressure

Table 2. List of models, elements and parameters used in different numerical simulations

## 6. EXPERIMENTAL

In this section, we report the different manufacturing parameters, specificities of the experiments, and major conclusions for each team. A table is provided, summarizing the main data of the machines adapted to WJISF.

In 2001, Iseki from Team 1 carried out a preliminary study based on a new flexible and lubricant-free incremental WJ sheet metal bulging method that avoided tool marks on the surface of nonsymmetrical shallow aluminum shells [3]. Iseki described his *homemade* WJ incremental bulging machine. The nozzle was attached to a traveling arm that was fixed in position by manually tightening clamping screws. The computer-controlled bulging machine shaped a wide range of complex shapes of sheet metal, including pyramidal shells, shells of pyramid frustums, shallow pans, and embossed panels. It was generally recognized that the ball bearing die allowed the bulge height of the shells to be controlled during shaping, using the high-speed WJ. In 2007, Iseki and Nara worked on WJISF of stainless-steel sheet metal [4]. They investigated the forming feasibility of a *static* shot peening method. After determining the perforating time limit, they investigated the influence of pressure and nozzle height on the jet thrust, measured using a load cell. They concluded that the jet thrust was in

proportion to the pump pressure, and independent of the stand-off height of the mixing nozzle and the mixing mass rate of metal balls.

In 2006, Team 2 defined technological windows as ranges of parameters (water pressure, WJ diameter, blank thickness, stand-off distance, etc.) that allow for workpiece plastic deformation without local erosion of the surface [5] [6]. Technological windows can be illustrated by plotting the surface erosion and plastic deformation limits on a parameter map. The researchers used a dedicated machine developed at Ljubljana University with a high-pressure pump capable of delivering a constant flow of 50 l/min at maximum pressure 20 MPa, a table with a working area of 400 × 400 × 400 mm, and a CNC controller. The blank was fixed in a workpiece holder inserted in a frame inside the working table. They compared ISF with a rigid tool and WJISF, in collaboration with Dortmund University (Germany). They concluded that WJISF can be used to complement ISF. They produced some basic geometric forms (square, circle, and triangle) with WJ without the use of a die. They noted that the jet diameter in abrasive WJ cutting is normally between 0.5 and 1.2 mm, water pressure up to 400 MPa, and water flow around 2 l/min. In WJISF, the jet diameter is around 2 mm, water pressure up to 25 MPa, and water flow about 50 l/min. The energy involved is within the same range in both processes, but the latter differ on WJ concentration. A WJ cutting machine pump cannot therefore be used to achieve WJISF. In 2008, Jurisevic et al. introduced laminated supporting tools into the WJISF process [7]. Their experimental work was performed on the dedicated machine described earlier. They studied the influence of different WJ trajectories (from parallel trajectories to ones geometrically close to the expected form trajectories) on forming accuracy. They observed that despite the use of a supporting tool, shape-specific trajectories had to be used to reduce geometric deviation. They also observed the benefits of using a supporting tool to improve accuracy. As laminated supporting tools are relatively easy to produce and do not substantially increase the total cost and time, it is quite relevant to use them. In 2009, Petek et al. compared rigid tool single point incremental forming (RTSPIF) and WJ single point incremental forming (WJSPIF) by means of technological windows. These showed the optimum operating area depending on workpiece material properties and part geometry

requirements [8]. Additionally, Petek et al. studied the influence of path trajectory parameters for shaping a square base pyramid as shown on Figure 6. Their experimental work was performed on the same dedicated machine as before. Their investigations led them to conclude that RTSPIF is more appropriate in the case of larger wall angles and smaller horizontal steps, while WJSPIF is a better choice for larger horizontal steps and smaller wall angles. RTSPIF also allows for greater process accuracy and shorter machining times than WJSPIF.

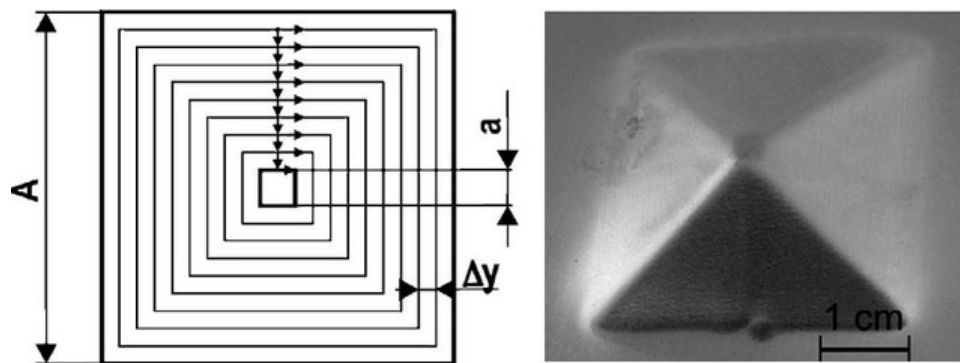


Figure 6. Observed tool trajectory and a formed feature during the experiments [8]

In 2010, Team 4 started their WJISF research by establishing a simulation model with mesh generation, boundary condition and constraint to calculate the deformation degrees [12]. They then compared the simulation results with the experimental ones. The case study in this paper concerned the WJ forming of a circular truncated cone by means of a cylindrical supporting tool. The simulation model was closely correlated with experimental results. In 2011, the team developed an experimental forming device to study the influence of WJ pressure, sheet metal thickness, and target distance on formability [13]. They observed that within the studied range, increased WJ pressure improved formability. By contrast, increasing nozzle distance reduced plastic deformation. They also noted that sheet metal thickness considerably influenced formability.

Team 5's experimental contributions are quite recent. In 2017, Lu et al. designed and developed a prototype machine system shown on Figure 7 that allowed both WJISF and ISF [15]. They observed that the surface obtained by WJISF had a better finish (less amplitude between peaks and valleys) than that obtained with ISF. For the ISF cone, even with the use of a lubricant, tool marks were clearly

visible, owing to the tool scratching the sheet surface. They observed that if the forming pressure produced by WJ was too high, it could cause high levels of deformation in a localized area, resulting in wrinkling of the formed parts. In 2018, Shi et al. experimentally studied the effects of WJ pressure, relative WJ diameter, sheet thickness, and feed rate on the surface finish of microformed stainless-steel foils [16]. They observed that the wall angle increased linearly with WJ pressure. The corresponding surface roughness first decreased then increased, owing to wrinkles on the surface. Reducing the incremental step improved surface finish and allowed for larger wall angles. The latter could also be obtained by reducing the feed rate. The researchers also investigated the influence of relative WJ diameter on formability and surface finish. In 2019, they carried out a further investigation through an FEA simulation of the process [17] and compared it with experiments such as the ones described in their previous publication. Truncated cones were formed from 316 stainless-steel foils 50.8  $\mu\text{m}$  thick by high-speed micro-WJs, whose diameter varied from 76.2 to 203.2  $\mu\text{m}$ . An experimental parametric study and a numerical model in Abaqus software were performed. The model was closely correlated with their experimental results for most of the parameter settings. In 2019, Shi et al. studied the WJISF process with several types of micromachined supporting dies to produce microscale shell parts with designed geometries [18]. The manufacturing strategy was shown to have a profound impact on the final geometry of the part, even with the same supporting die. The experimental results suggested that tool paths and supporting die geometry should be defined according to the expected part shape. Compared with dieless WJISF, this study showed that the geometric accuracy of the part is improved by using supporting dies. However, toolpath definition is critical for achieving highly accurate parts with excellent surface quality.

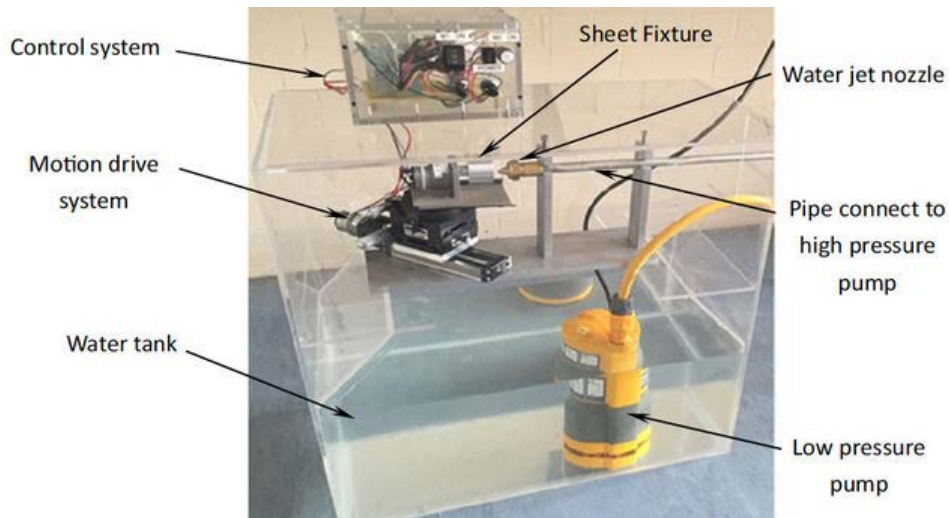


Figure 7. Developed WJISF prototype machine [15]

In 2011, Team 6 ran a theoretical versus experimental comparison of a metal sheet deformed by WJ impact loading [19]. In 2013, He et al. studied the influence of pressure, feed rate and incremental step on the formability of WJISF [22]. Along a single linear tool path, they observed that increasing pressure increased deformation depth almost linearly. They also observed that even if feed rate varied, forming depth remained constant until a threshold was reached, and then dropped significantly. They used a concentric toolpath strategy to form truncated cones to investigate the influence of incremental steps on forming depth. They observed that depth achieved for a single incremental step decreased with the number of steps: the depth measured for the first step was 0.75 mm, whereas the depth obtained for the final 30<sup>th</sup> step was 0.54 mm. They concluded that formability can be improved by two methods: increasing WJ pressure during the forming process or decreasing the incremental step values. In 2014, H. Li et al. compared spiral versus concentric toolpath strategies for forming truncated cones [25]. They concluded that a spiral trajectory yields a better visual appearance, especially when the spiral starts from the outside and moves toward the inside. The same year, J. Li et al. proposed a geometric model of the relationship between flow pressure and the wall angle of truncated cones [24]. They correlate their model with experimental results and obtained a good match. They concluded that wall angle increases with water pressure within a range defined to observe yield at the lowest-pressure value and avoid tearing at the highest-pressure value.



In 2016, Teymoori et al. in Team 9 simulated the whole deformation process of a conical part with WJISF, using a three-dimensional FEA method [32]. To verify the accuracy of the simulation results, experiments were carried out with an annealed copper sheet. The numerical and analytical results were generally in good agreement with the experimental ones.

Table 3 summarizes the main characteristics of the machines developed by the different teams to conduct their experiments.

Team	Machine type	Maximum Pw (Mpa)	Maximum flow rate (L/min)	Maximum travelling speed (mm/s)	Strokes x y z (mm)
T1	Homemade (01)	19.6	15	10	160x280x100
T1	Homemade (07)	20	6.1	2.5RPM + 0.26	100x360°x100
T2	2-axis CNC + manual vertical axis	20	50	1.67	400x400x400
T4	DK7735 wire-cutting machine based	35	63.3	10	350x450x350
T5	Homemade 1	10	8.33		2 dof
T5	Homemade 2	450		40	
T6	3-axis CNC based + 2 dof* nozzle system (rotary X and Z)	120	30	1000	5 dof
T9	3-axis CNC with a rotary table	30	50		

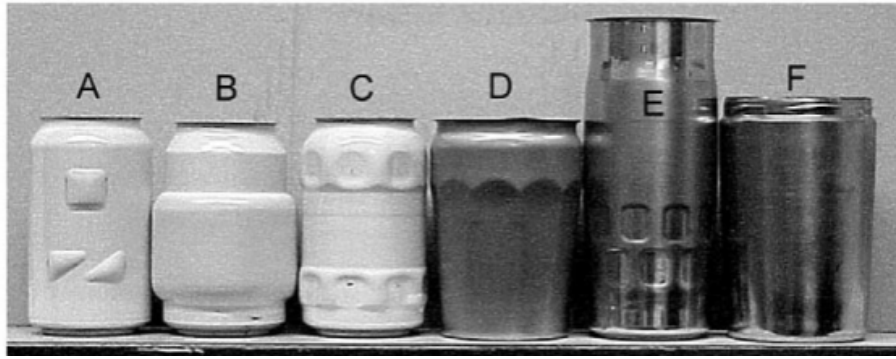
Table 3. List of the main characteristics of the different machine tools (dof = degrees of freedom).

## 7. REAL-WORLD PART MANUFACTURING

*Real-world parts* refer to geometries and materials that could correspond to industrial requirements. They contrast with test parts, which are simple features produced in order to test a few specific characteristics, as described in the previous section. Of course, during the preliminary study of an innovative process, test parts are manufactured before real ones. However, to bring the process to an industrial level, real-world parts must be manufactured, in order to check productivity (time, cost, and quality).

The two papers published by W.C. Emmens from Team 3, focused on real-world part manufacturing. WJ forming was investigated for shaping steel beverage cans. After deep drawing and wall ironing, cans may require a fanciful shape, and this can be achieved with WJISF, using rotating nozzles inside the can to push the wall outwards. The general characteristics of the process were defined in the first paper [10], with tests conducted on a variety of cans shown in Figure 8. They were then compared with results published in the literature on incremental forming with a steel punch or roller in the second paper [11]. The main differences between WJ forming and mechanical incremental forming (with a steel punch or roller) were:

- WJ forming is basically a force-controlled process; the final shape being determined by the molds (dies) that are used. This eliminates the need for a numerical control system, making it simple and cheap and very fast. However, a mold is required for each shape.
- Mechanical incremental forming is basically a displacement-controlled process. This eliminates the need for a mold (although one is sometimes used) but requires a numerically controlled punch. The equipment is expensive and slow.



*Figure 8. Products produced by water jet forming. Types A and B have no commercial application and were used for testing only. Note the screw thread at the top of Type F that was formed during the same operation. Types A, B, C, and E were manufactured from standard 66-mm diameter cans [10]*

Although the use of WJ seems very promising, as reported by W.C. Emmens (high-speed process, no friction because no punch-sheet contact), the geometries of the real-world parts allowed very small rotating nozzles to be used, and the results could not be reproduced in non-axisymmetric sheet-metal forming.

Team 6 also investigated real-world part manufacturing, in parallel with more classic numerical and experimental studies. They presented WJ multistage incremental forming strategies for producing a metal bellow [26]. The nozzle that rotated around the axis of the tube was guided by an NC program, and no die was needed. Meanwhile, to guarantee the quality of the bellow forming, axial compression was required. Exactly like the process used by Team 3 for shaping cans, the nozzle induced a columnar high-pressure WJ that sprayed against the tube wall, causing plastic deformation at the point. As the nozzle moved vertically at a constant speed, the point of impact of the WJ traveled over the tube in a spiral trajectory. The resulting metal bellow is shown in Figure 9. Some complex workpieces were carried out by Team 6 [23-25], using the same 5-axis machine, but without any explanations or analysis about materials or dimensions, which is why they are not discussed at greater length in this section.



Figure 9. Manufactured metal bellow [26]

Team 5 recently published [17] an experimental and numerical study of dieless WJ incremental microforming. To demonstrate the flexibility of the process, several complex shapes were formed in stainless-steel foil 50.8  $\mu\text{m}$  thick. Figure 10 features CCD camera images of a two-level cone, microchannels, and three individual letters. Results showed that miniature shell products with complex shapes can be produced by WJ incremental sheet metal microforming.

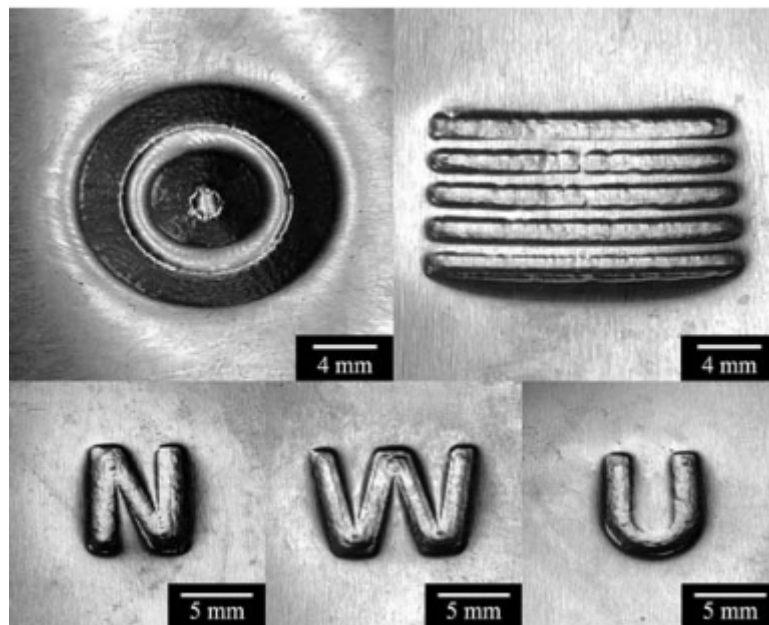


Figure 10. CCD images of complex geometries [17]

A full list of published reports about real-world part manufacturing by WJISF is provided in Table 4, which indicates the geometry and material for each team.

Team / Ref.		Geometry	Material
T3	[10,11]	Beer and beverage can	ASTM A517 Low-alloy steel Grade P, Grade Q
T5	[17]	Two-level cone, channels, letters	Stainless steel (50.8 $\mu\text{m}$ )
T6	[26]	Bellow	Stainless steel 304

Table 4. Full list of real-world parts manufactured by WJISF

Similarities across these different studies lead us to three main conclusions about potential further industrial development:

- Only steel has been used for real-world part manufacturing. Although several experimental and numerical studies have focused on aluminum, copper and titanium alloys, the industrial applications of WJISF may mainly be in steel.
- The three applications concentrated on a small deformation of a preformed part: shaping of beverage cans, local plastic deformations of a tube to produce a bellow, and microforming. None of the studies produced parts in a full design and manufacturing process (requirements, design, manufacturing, control), so WJISF is still seen as a prototyping process.
- For industrial applications, productivity must be studied in terms of cost and quality. This is clearly yet to be done. Quality indicators, such as dimensional accuracy and surface roughness, are often simulated, but have not so far been controlled in studies of real-world parts.

## 8. SUMMARY & DISCUSSION

As can be seen in the previous sections, although WJISF is seen as a very promising process, many experimental and numerical studies still need to be carried out before it can be scaled up for manufacturing. Manufacturing parameters must therefore be defined for further studies.

In order to produce this state-of-the-art review, we devised new technological windows based on scientific data, showing the boundaries of the forming process with regard to its parameters. Further investigations should be encouraged, as these windows would benefit from additional experimental or numerical studies.

The technological windows contain quantified data to help engineers experiment with this process or undertake real-world part manufacturing. They should also encourage scientists to carry out further experimental or numerical research to add to the state of the art. Figure 11 shows the method we defined and followed to obtain the technological windows, and Figure 12 presents the different technological windows for aluminum, copper and iron alloys.

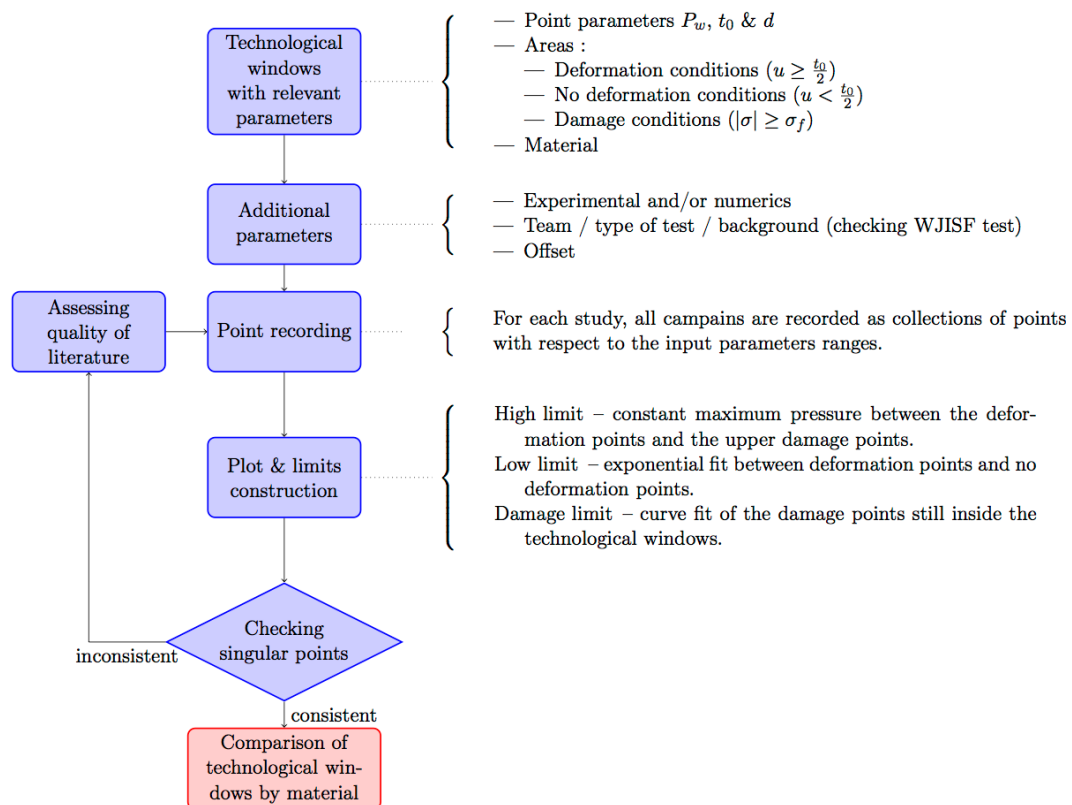


Figure 11. Methodology for creating technological windows for an innovative process ( $k;p_w$ ).

The first stage for obtaining the technological windows was the extraction of the manufacturing parameter values. As defined in Figure 1, the main parameters were pump pressure  $p_w$ , canon diameter  $d$ , and sheet thickness  $t_0$ . Material was also an important input parameter, and was divided into “Iron alloys”, “Aluminum alloys”, “Copper alloys”, and “Other”. Owing to the lack of data, the last

category (e.g., titanium alloy [14]) was not explored further, so only three windows were plotted for material. Based on earlier work by Team 2 [5] [6], we introduced relative jet diameter  $k$ . This nondimensional number was defined as WJ diameter (estimated by  $d$ ) over initial blank thickness  $t_0$ , as follows:

$$k = \frac{d}{t_0}$$

Next, for the different manufacturing parameters provided by the different teams, we defined three forming modes:

- Deformation conditions, if the sheet is plastically deformed without damage.
- No deformation conditions if the vertical displacement is below  $0.5 \times t_0$ ;
- Damage condition if the stress is higher than failure limit  $\sigma_f$ .

Some additional parameters were also listed, such as numerical or experimental values. This enabled all the necessary information to be collected to build the whole database. In the third and fourth stages, the points were recorded and plotted in the technological windows. Then, for each material, three limits were plotted: a constant high limit, an exponential low limit, and a damage limit. In the case of outliers, the authors of the studies were asked to check their values and, if needed, correct them. We then plotted Figure 12, to compare the technological windows material by material.

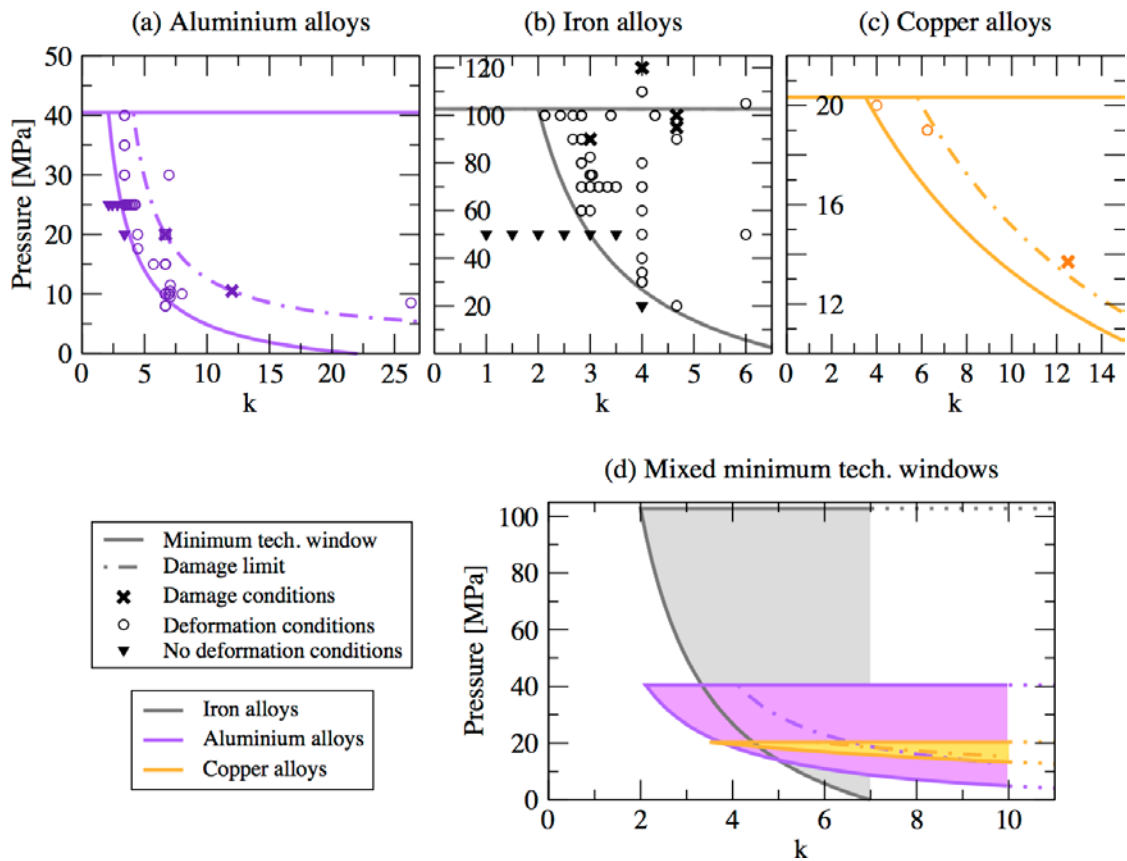


Figure 12. Technological windows for (a) aluminum alloys, (b) iron alloys, and (c) copper alloys, and (d) minimum technological windows for all three materials.

By integrating data from the literature into Team 2's technological windows, we were able to define an area that corresponded to a set of parameters for which WJISF is achievable. Each of these minimum technological windows was built by minimizing a classic WJISF domain with respect to published data. However, care must be taken regarding the number of experimental points used to define the boundaries. For aluminum and copper alloys, some operating parameter values lead to workpiece damage, even though they are within the WJISF achievable area. This observation raises the question of a second damage boundary limit that is not pressure-only dependent. As only a couple of values have been found to lead to damage, further investigations need to be carried out. Additional data would improve these technological windows. The authors warmly welcome contributions that can help to define the boundaries more accurately.



## 9. CONCLUSION AND PERSPECTIVES

As can be seen here, an eclectic range of industries (e.g., automotive, micro-electronics, medical and aerospace) could be concerned by the WJISF process. Like ISF, WJISF requires a multi-axial machine (CNC or robot), as well as a pressure pump with a sufficient flow rate and pressure (as shown in Table 3). From an environmental point of view, this can be seen as a *green* process, given that the water can be recycled and there is no lubricant. WJISF could thus be a useful process with considerable potential for development in the future.

For 20 years, scientists all over the world have been investigating this process from different angles. Many simple tests (impacts, grooves, cone frustum) have been carried out, with numerical and experimental comparisons. Nevertheless, few real-world parts have been manufactured, and the full complexity of the shapes obtained with WJISF has yet to be explored. The technological windows in Figure 12 also show that iron and aluminum alloys are the main materials that have been studied so far. Although there are some data for other metal alloys, more investigations are needed. Moreover, the forming limits provided here should be refined by other data.

The present review provides an interesting summary and possible answers to the main questions concerning researchers, technological feasibility, numerical simulation, machine tools, and real-world parts). Table 1, Table 2, Table 3, Table 4 and Figure 12 provide a succinct yet comprehensive state of the art, and will help both scientists and manufacturers find WJISF parameters that match their needs. This state of the art was established by applying a rigorous and systematic approach described in Figure 2. The same methodology could be applied to other innovative manufacturing processes to provide a full description of their main characteristics.

### DECLARATIONS

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The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

b. Conflicts of interest/Competing interests (include appropriate disclosures)

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The authors have no affiliation with any organization with a direct or indirect financial interest in the subject matter discussed in the manuscript

c. Availability of data and material (data transparency)

The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

d. Code availability (software application or custom code)

Not applicable

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Not applicable

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