Technical White Paper on Integrated Weld-free Exhaust Pipe Bending Process

—— Integrated Tube Forming Solution for Stainless Steel/Titanium Alloy Thin-walled Exhaust Pipes of Motorcycles and Automobiles

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Abstract

Motorcycle and automobile exhaust pipe products have four typical process characteristics: small bending radius (R/D ≤ 1.5), thin wall thickness (t/D ≤ 0.05), high-performance materials (304/316L stainless steel, Gr.2/Gr.9 titanium alloy), and extremely short straight sections between two bends (even approaching zero). The traditional solution adopts the "prefabricated elbow + welding splicing" production method. Although the process is simple, there are inherent defects such as corrosion in the heat-affected zone of the weld, airflow turbulence, reduced fatigue life, poor appearance consistency, and high post-processing costs.

This white paper, based on years of engineering practice by the tube bender manufacturer SANCO GROUP (www.sancomachine.com), systematically describes an integrated weld-free Rotary Draw Bending (RDB) forming solution for exhaust pipes. The solution achieves defect-free forming of thin-walled, difficult-to-deform materials under extreme conditions of 1D ≤ R ≤ 1.5D, t/D ≤ 0.05, and straight section L ≤ 0.5D through the collaborative application of five key process technologies: C12 carbide bending die, multi-ball flexible mandrel, copper wiper die, anti-slip serrated clamping die, and dual-layer conformal clamping die. The paper provides recommended values for core process parameters, die material selection criteria, process flow, and quality control solutions, offering a replicable technical path for exhaust pipe manufacturing enterprises to achieve "weld-free, lightweight, and integrated" upgrades.

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1. Introduction

1.1 Industry Background

Driven by the global "Dual Carbon" strategy and the trend of lightweighting in motorcycles and automobiles, high-performance exhaust systems, as one of the key components of the powertrain, are rapidly evolving towards thin walls, lightweight, high corrosion resistance, and high-quality appearance. Taking a typical high-end motorcycle mid-to-rear exhaust pipe as an example, its outer diameter is usually ϕ38 ~ ϕ60 mm, the wall thickness has decreased from 1.5 mm to 0.8 ~ 1.0 mm, and the material has been upgraded from ordinary carbon steel to 304, 316L stainless steel, or even Gr.2 pure titanium or Gr.9 titanium alloy; meanwhile, to achieve the optimal exhaust flow path within limited chassis space, pipe parts generally have multiple small-radius bends close to each other, with almost no straight transition between bends.

1.2 Inherent Defects of Traditional Welding Process

Faced with these severe geometric and material constraints, the industry commonly adopts a segmented manufacturing solution of "prefabricated elbow + straight pipe section + manual/automatic welding splicing". This solution has the following non-negligible technical and economic defects:

No.	Defect Category	Manifestation	Consequence
1	Metallurgical Defect	Grain coarsening & sensitization in welding Heat Affected Zone (HAZ)	Intergranular corrosion resistance reduced by 30 ~ 50%
2	Stress Concentration	Porosity & incomplete fusion easily formed at weld root	Fatigue life decreased by over 40%
3	Turbulent Flow Field	Internal protrusion & misalignment at weld seam	Higher exhaust backpressure and engine power loss
4	Poor Appearance Consistency	Color difference & oxidation rings on welds	Secondary polishing / electrolytic finishing required for high-end vehicles
5	High Overall Cost	Multiple processes: welding, shaping, grinding, air tightness test	Unit cost increased by 20 ~ 35%
6	Difficult Welding of Titanium Alloy	Titanium absorbs oxygen & hydrogen under high temperature leading to embrittlement	Welding must be carried out in inert gas sealed chamber with extremely low efficiency

1.3 Core Proposition of This Solution

Can a single tube bender, a single tube, and a single clamping be used to bend the entire section of the exhaust pipe into shape, completely eliminating welds?

The answer is yes. This white paper will systematically demonstrate that: as long as targeted designs are carried out in the four key dimensions of die material selection, mandrel design, wrinkling inhibition, and clamping method, integrated forming of thin-walled, difficult-to-deform materials can be stably achieved with small radius, short straight sections, and multiple bends.

Figure 1 intuitively presents the appearance comparison between traditional welded exhaust pipes and integrated forming exhaust pipes.

Figure 1 Appearance Comparison between Traditional Welded Exhaust Pipe (Left) and Integrated Weld-free Exhaust Pipe (Right) ——© SANCO GROUP · www.sancomachine.com

📽 Video 1: Performance Comparison Demonstration between Welded Exhaust Pipe and Integrated Forming Exhaust Pipe

(Video placeholder and QR code reserved here. Recommended video content: weld cross-section of two exhaust pipes + back pressure test bench data comparison.)

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2. Analysis of Difficulties in Exhaust Pipe Bending Process

Before introducing the solution in depth, it is necessary to clarify the four difficulties of exhaust pipe bending at the mechanical level, which are the starting point for all process designs in this white paper.

2.1 Strain Concentration Caused by Small Bending Radius

During the bending process, the outer wall of the pipe bears tensile stress, the inner wall bears compressive stress, and the stress is smallest near the neutral layer. The maximum tensile strain of the outer wall can be approximately expressed as:

Where R is the bending centerline radius and D is the pipe outer diameter. When R/D = 1 (i.e., 1D bending), ε = 50%, which has far exceeded the safety margin of the uniform elongation of about 45% for 304 stainless steel, easily leading to thinning and cracking of the outer wall; at the same time, the compressive strain of the inner wall causes material instability and wrinkling. For every 1D reduction in bending radius, the forming difficulty increases non-linearly.

2.2 Cross-sectional Collapse Caused by Thin Walls

The ability of a pipe to resist cross-sectional deformation is proportional to the cube of the wall thickness. When $t/D \le 0.05$ (e.g., ϕ50 × 1.0 mm pipe), the inner wall of the bending zone is prone to collapse into the pipe cavity under pressure, forming "cat-back" or ovalization defects; meanwhile, the thinning of the outer wall causes the cross-section to show typical pear-shaped distortion, directly affecting the exhaust flow area and appearance quality.

2.3 High Deformation Resistance Caused by Materials

304 stainless steel has a yield strength ≥ 205 MPa and a tensile strength ≥ 520 MPa; Gr.9 (3Al-2.5V) titanium alloy has a yield strength ≥ 620 MPa and significant work hardening, requiring extremely high die hardness and surface finish. In addition, titanium alloys have a serious tendency to stick to the die, easily forming cold welding in the die groove, leading to surface scratching of the pipe part.

2.4 Insufficient Clamping Length Caused by Short Straight Sections

Theoretically, the effective clamping length of the clamping die for rotary draw bending should be ≥ 2 ~ 3 times the pipe diameter to ensure no slipping under the maximum bending moment. However, the straight section L between two bends of the exhaust pipe is often less than 1D, and some designs even have L ≈ 0. At this time, no matter how the ordinary flat groove clamping die is designed, it cannot provide enough clamping area, and tangential slipping will inevitably occur during the bending process, leading to loss of control of the bending angle and tensile cracking of the outer wall.

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3. General Technical Solution for Integrated Weld-free Pipe Bending

In response to the above four difficulties, this solution (proposed by SANCO GROUP) constructs a systematic technical system of "one machine, two dies, and three controls":

One machine: High-rigidity CNC Rotary Draw Bender (RDB), spindle torque ≥ 8000 N·m, repeat positioning accuracy ± 0.05°;

Two dies: C12 carbide bending die as the active actuator, and copper wiper die as the passive inhibitor;

Three controls: Shape control —— Multi-ball flexible mandrel for cross-sectional geometric control;
Stability control —— Wiper die + boosting device for instability inhibition;

Clamping control —— Anti-slip serrated / dual-layer conformal clamping die for stable clamping of extremely short straight sections.

The collaborative relationship between the five key technologies can be summarized in the following table:

Process Difficulty	Leading Solution Technology	Auxiliary Technology
Small bending radius → wrinkling	Copper wiper die	Precise adjustment of mandrel overhang
Thin wall → cross-section collapse	Multi-ball flexible mandrel	Rear booster force
High-strength material → die wear & cold welding	C12 cemented carbide bending die	TiN / DLC surface coating
Ultra-short straight segment → clamping sliding	Anti-slip serrated clamp die + dual-cavity conformal clamp die	Increase clamping pressure

The function principles, design points, and implementation precautions of the five key technologies are described in detail in the following chapters.

4. Detailed Explanation of Key Process Technologies

4.1 C12 Carbide Bending Die: Die Selection for High-strength Materials

4.1.1 Material Selection Logic

The bending die is the core actuator with the most complex stress and most serious wear among all dies of the tube bender. Its inner groove needs to slide relatively with the pipe part under huge contact stress. If the die hardness is insufficient, failure modes such as groove collapse, edge peeling, and surface scuffing will quickly appear. A comparison of common materials for bending dies and their characteristics is as follows:

Material	Rockwell Hardness (HRC)	Impact Toughness	Wear Resistance	Processing Cost	Application Scenario
45# Medium Carbon Steel	25 ~ 30	★★★★★	★	Low	Prototype trial, soft copper/aluminum tubes
42CrMo Alloy Steel	38 ~ 42	★★★★	★★	Medium	Ordinary carbon steel tubes
Cr12MoV Tool Steel	55 ~ 60	★★★	★★★★	Medium-High	Mass production of stainless steel parts
C12 (WC-Co Cemented Carbide)	≥ 88 (HRA) / Equivalent to approx. 72 HRC	★★	★★★★★	High	Thin-wall stainless steel & titanium alloy tubes

C12 is a typical medium-cobalt (Co content 6 ~ 10%) tungsten-cobalt carbide grade (belonging to the K-class general tool carbide system). Its macro hardness reaches above HRA 88 (far exceeding the HRC

60 of alloy tool steel), and its wear resistance is about 5 ~ 8 times that of Cr12MoV; meanwhile, its bending strength can reach 2500 ~ 3000 MPa, enough to withstand contact pressure of several tens of kN during the bending process of thin-walled stainless steel pipes.

4.1.2 Structural Design Points

Groove radius matching: Groove radius = 0.5D + 0.02 ~ 0.05 mm (negative tolerance compensation), to avoid pipe "lifting";

Groove surface roughness: Ra ≤ 0.4 μm, mirror polishing; for titanium alloys, TiN / DLC coating should be further applied to reduce the friction coefficient to below 0.1; clamping die, wiper die, and pressure die are upgraded simultaneously; since the hardness of the C12 bending die is much higher than that of the mating dies, if the mating dies are still made of ordinary steel, they will be worn by the C12 in reverse, so it is recommended to configure carbide for key parts in sets;

Heat treatment and inlay process: C12 material is brittle, so a composite structure of steel base + carbide inlay is usually used to balance hardness and impact resistance; the inlays are fixed by high-temperature brazing or precision bolts for easy local replacement.

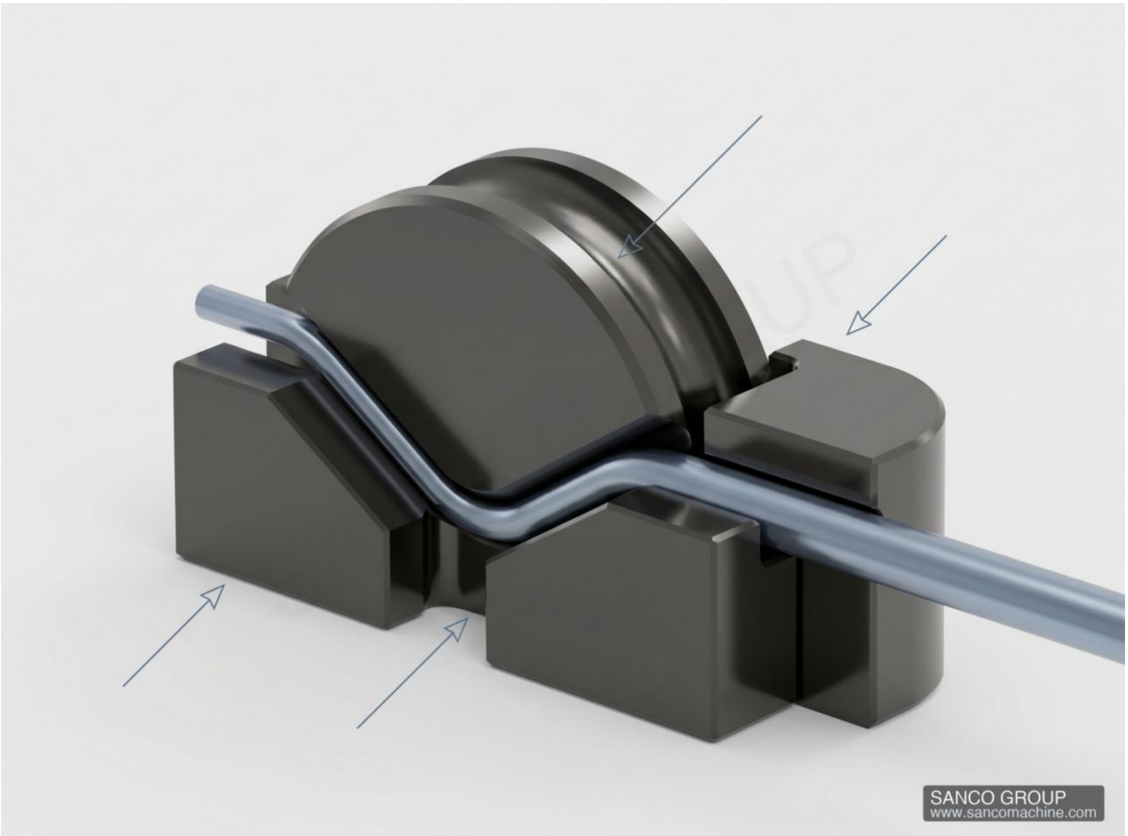

Figure 2 Cross-sectional Rendering of C12 Carbide Bending Die (Including Bending Die, Clamping Die, and Pressure Die Set) ——© SANCO GROUP · www.sancomachine.com

📹 Video 2: Demonstration of Assembly and Commissioning of C12 Carbide Die

(Video placeholder and QR code reserved here. Recommended video content: the complete process from unpacking, installation, centering to trial bending of the die.)

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4.2 Multi-ball Flexible Mandrel: Preventing Thin-wall Collapse and Cross-sectional Distortion

4.2.1 Mechanical Role of the Mandrel

The mandrel is the core internal support element for controlling the cross-sectional shape of thin-walled pipes. Its essence is to provide a rigid support surface close to the inner diameter of the pipe inside the bending zone cavity, resisting the inward collapse force of the inner wall and constraining the ovalization tendency of the outer wall.

4.2.2 Mandrel Type Selection

Mandrel Type	Structure Description	Support Capacity	Applicable R/D	Remarks
Solid Plug Type	Single-head cylinder	Weak	≥ 3D	Only for thick-wall tubes
Single-ball Type	1 single ball	Medium	2D ~ 3D	Medium wall thickness tubes
Multi-ball Type (3 ~ 5 balls)	Multiple balls connected in series with hinges	Strong	1D ~ 1.5D	First choice for thin-wall exhaust pipes
Flexible Cable Type	Built-in steel cable chain	Ultra-Strong	0.8D ~ 1D	For extreme working conditions

For typical 1D ~ 1.5D small radius + thin wall conditions of exhaust pipes, a 3 ~ 5 ball flexible mandrel is recommended. The empirical formula for calculating the number of balls is:

Where θ is the bending angle (in radians), R is the bending radius, and P is the pitch between balls (generally 1.0 ~ 1.2 D).

4.2.3 Key Parameters of the Mandrel

Ball diameter tolerance: D_ball = D_inner − (0.15 ~ 0.25) mm, i.e., the mandrel clearance is controlled at 0.15 ~ 0.25 mm; excessive clearance → collapse out of control, too small clearance → scratching/jamming;

Pitch (Lead): The forward distance of the mandrel head relative to the tangent point, usually e = (1/3 ~ 2/3) · D; excessive lead leads to excessive thinning of the outer wall, and too small lead leads to inner wall wrinkling;

Mandrel material: The body is recommended to be SKD11 or H13 quenched to HRC 58 ~ 62, with TiN / CrN / DLC coating, friction coefficient ≤ 0.15;

Lubrication method: Titanium alloy bending must use high-pressure extreme-pressure bending oil, continuously supplied to the bending zone through the inner hole of the mandrel rod.

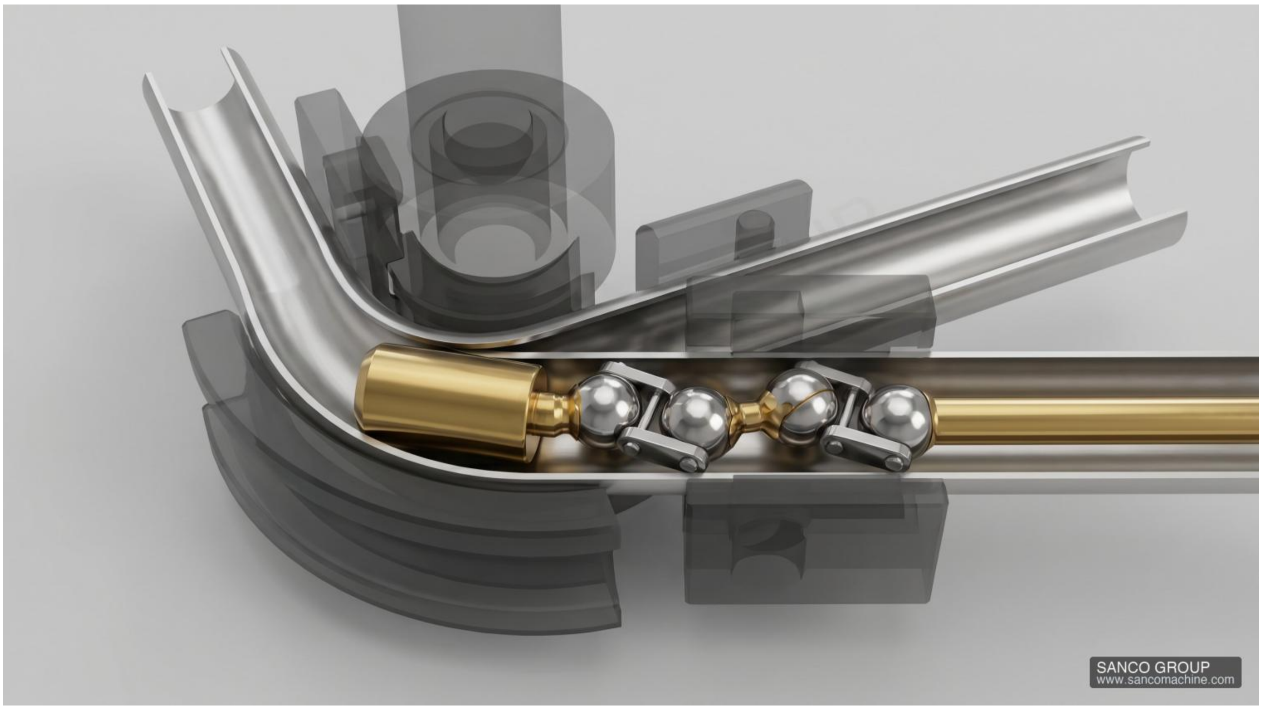

Figure 3 Schematic Diagram of Multi-ball Mandrel (Multi-ball Mandrel) Working Inside a Thin-walled Pipe (Pipe Body Section Shows Internal Structure) ——© SANCO GROUP · www.sancomachine.com

📹 Video 3: Actual Working Process of Multi-ball Mandrel in Thin-walled Stainless Steel Pipe

(Video placeholder and QR code reserved here. Recommended video content: transparent die test or industrial endoscope real shot.)

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4.3 Copper Wiper Die: Inhibiting Wrinkling Defects in Small Bending Radius

4.3.1 Wrinkling Mechanism

In small R/D bending, the material on the inner side of the bending zone is subjected to tangential compressive stress. Once the compressive stress exceeds its critical instability value, longitudinal wave-like wrinkles appear. Theoretically, the critical condition for pipe instability and wrinkling is approximately:

Where K is the constraint coefficient (generally 0.6 ~ 1.2) and E is the elastic modulus. When t/D is extremely small and R/D is extremely small, σ_cr drops sharply, and wrinkling is almost inevitable.

4.3.2 Working Principle of the Wiper Die

The wiper die is a wedge-shaped tool installed behind the bending tangent point and fitting the inner bend side of the pipe. Its function is to press flat and "scrape away" the wrinkles at the moment they just begin to sprout, thereby preventing the wrinkles from continuing to develop and accumulate in the bending zone.

4.3.3 Why Choose Copper (Bronze / Beryllium Copper)?

Material	Hardness (HB)	Friction Coefficient	Risk of scratching titanium/stainless steel	Conclusion
Hardened Steel	350 ~ 450	0.25 ~ 0.35	High Risk	✗ Not recommended
Aluminum Bronze QAl9-4	170 ~ 200	0.10 ~ 0.15	Low Risk	✓ Recommended
Beryllium Bronze QBe2	≈ 380	0.08 ~ 0.12	Low Risk	✓ Highly recommended (for titanium alloy)
MoS_2 / Graphite Composite Coating	—	0.05 ~ 0.08	None	✓ Auxiliary surface coating

The key advantage of copper alloys over quenched steel is that they do not leave scratching marks on the surface of stainless steel and titanium alloys, while their self-lubricating properties significantly reduce the tendency for inter-metal adhesion. Beryllium bronze (QBe2) is particularly outstanding in hardness and wear resistance, and is the preferred wiper die material for bending titanium alloy exhaust pipes.

4.3.4 Installation and Adjustment of Wiper Die

Tangent point alignment: The tip of the wiper die needs to be accurately aligned with the bending tangent point, deviation ≤ 0.1 mm;

Contact length: Generally 2~3D;

Fitting clearance: Clearance with the pipe wall 0.02 ~ 0.05 mm, "fitting loosely but clearly";

Rake Angle: 0° ~ 3°, slightly inclined towards the inner side of the pipe;

For titanium alloys: It is recommended to re-grind the tip every 500 ~ 1000 bends to ensure sharpness.

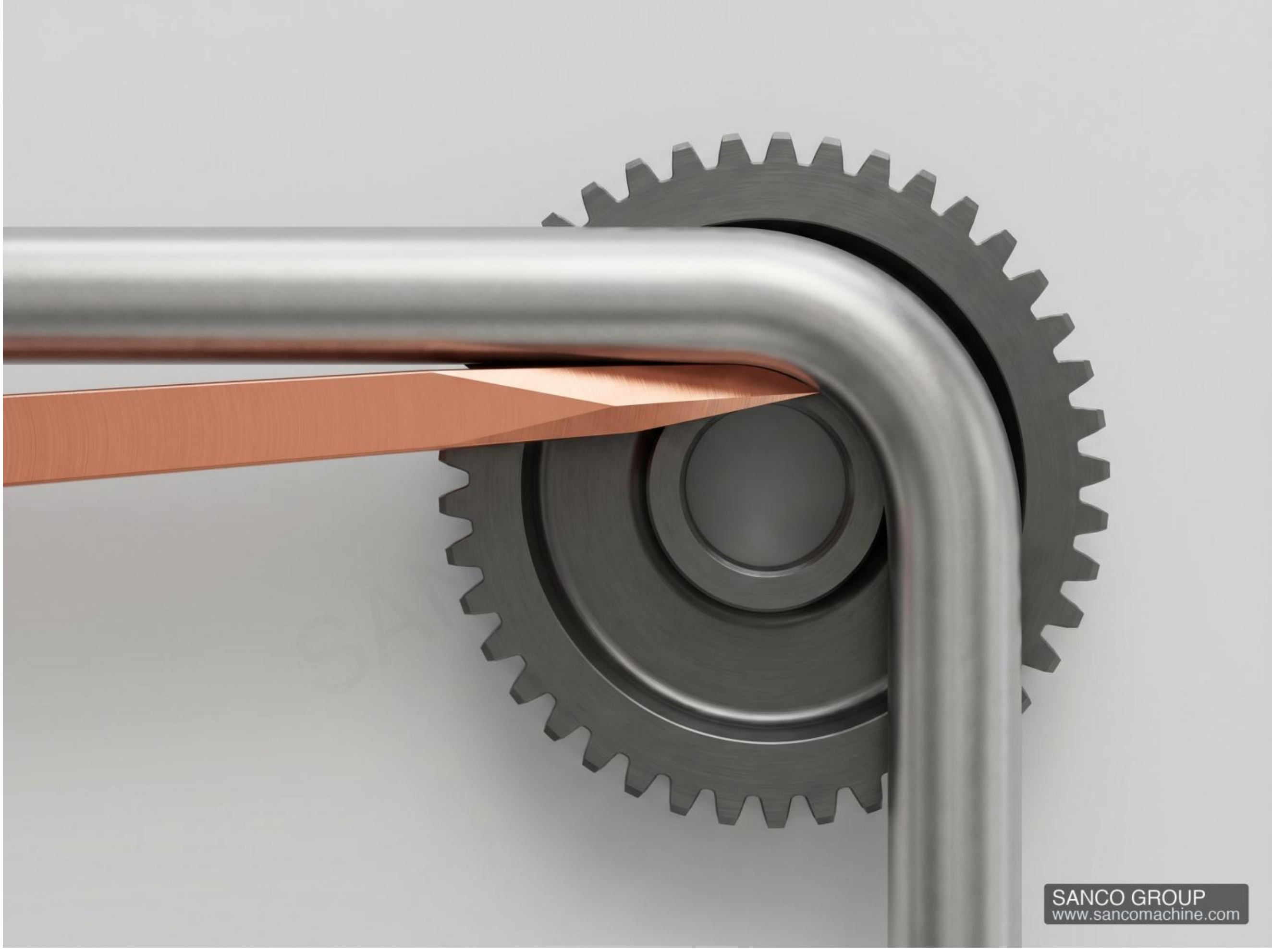

Figure 4 Schematic Diagram of the Position of the Copper Wiper Die in the Rotary Draw Bending Device ——© SANCO GROUP · www.sancomachine.com

📹 Video 4: On-site Adjustment Teaching of Wiper Die

(Video placeholder and QR code reserved here. Recommended video content: technician adjusting the wiper die clearance with a feeler gauge + comparison of trial bending effects.)

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4.4 Anti-slip Serrated Clamping Die and Dual-layer Conformal Clamping Die: Solving Clamping Challenges for Short Straight Sections

4.4.1 Physical Challenges of Short Straight Section Clamping

During the bending process, the clamping die needs to bear the bending tangential tension F_t and the resulting shear force. When the effective clamping length is insufficient, the friction between the clamping die and the pipe is not enough to resist the tangential tension, and the pipe is "pulled out", leading to:

- Insufficient bending angle;
- Excessive thinning of the outer wall and even cracking;
- The curvature of the previous bend being "pulled back" and distorted.

When the clamping area cannot be increased (limited by the geometry of the product's straight section), breakthroughs can only be made in two directions: ① Increase the equivalent friction coefficient μ; ② Change the clamping geometry so that the "already formed bend" also participates in clamping.

4.4.2 Solution A: Anti-slip Serrated Clamp Die

Precision-machined micro-triangular or diamond-shaped tooth patterns (tooth height 0.05 ~ 0.10 mm, tooth pitch 0.5 ~ 1.0 mm) on the inner groove surface of the clamping die create a micro-bite between the clamping die and the pipe wall, increasing the equivalent friction coefficient from 0.15 to 0.4 ~ 0.6, and increasing the clamping force by 3 ~ 4 times.

Tooth Pattern	Tooth Height	Tooth Pitch	Application Scenario
Straight Serrations	0.05 mm	0.5 mm	High surface finish requirement
Diamond Serrations	0.08 mm	0.8 mm	General recommended type
Triangular Cross Serrations	0.10 mm	1.0 mm	High torque, slight indentations acceptable

⚠ Note: The tooth pattern will leave micro-impressions on the outer surface of the pipe. For the exposed rear section of the exhaust pipe, it is recommended to perform anti-slip treatment first and then secondary polishing; for the middle section assembled inside the vehicle, it does not affect use at all.

4.4.3 Solution B: Dual-layer Conformal Clamping Die —— Core Innovation

When the straight section L between two bends is less than 0.5D, or even L ≈ 0 (i.e., the end of the previous bend is the starting point of the current bend), any straight groove clamping die cannot provide sufficient clamping area. At this time, the geometric form of the clamping die must be changed:

Core idea: Make the lower groove of the clamping die into a conformal groove exactly consistent with the previous formed bend, so that the "already bent part" is directly embedded in the clamping die and participates in clamping together with the new straight pipe section.

In this way, the equivalent clamping length is no longer limited by the "remaining straight section", but is extended to the entire arc length of the previous bend, providing 3 ~ 5 times the effective clamping area. Meanwhile, the upper groove retains the standard straight groove for clamping the unbent part.

Parameter	Recommended Value	Description
Height difference between upper and lower grooves	= D + 2 mm	Avoid interference between pre-bent tube segment and raw tube segment
Radius of conformal groove	Equal to previous bend	Must match product drawing in 1:1 scale
Wrap angle of conformal groove	Equal to previous bend	Normally effective when ≥ 45°
Material	Cr12MoV / C12	Same grade as main clamp die
Tooth pattern	Diamond anti-slip serrations can be superimposed	Optimal comprehensive performance

The greatest engineering significance of this solution is: it transforms "geometric conflict" into "geometric anchoring", making the most difficult short straight section condition actually have the strongest clamping capacity. This is the key key that enables the integrated weld-free solution advocated in this white paper to work for extreme exhaust pipe products.

Figure 5 Schematic Diagram of Dual-layer Conformal Clamping Die (Dual-cavity Conformal Clamp Die) Clamping Short Straight Section (L ≈ 0) Pipe Part ——© SANCO GROUP · www.sancomachine.com

📽 Video 5: Actual Bending Demonstration of Dual-layer Conformal Clamping Die on Short Straight Section Exhaust Pipe

(Video placeholder and QR code reserved here. Recommended video content: a complete shoot of the entire process from loading → the first bend → indexing → the second bend (no straight section).

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5. Recommendation of Process Parameters and Selection Reference Table

Based on the above analysis, this section provides recommended process parameters for typical exhaust pipe products under different material and geometric conditions for direct lookup in engineering implementation. The following parameter system is compiled by SANCO GROUP (www.sancomachine.com) based on years of production practice.

5.1 Material × Specification × R/D Comprehensive Selection Table

Material	**Typical Spec (D × t, mm)**	**Recommended R/D**	**Number of mandrel balls**	**Wiper die material**	**Clamp die type**	**Bending oil**
304 Stainless Steel	ϕ38 × 1.0	1.5	3 balls	Aluminum Bronze QAl9-4	Anti-slip serrated	General extreme pressure oil
304 Stainless Steel	ϕ50 × 1.0	1.2	4 balls	Aluminum Bronze QAl9-4	Anti-slip serrated + dual-cavity conformal	General extreme pressure oil
316L Stainless Steel	ϕ50 × 0.8	1.5	4 balls	Aluminum Bronze QAl9-4	Anti-slip serrated	Special oil for stainless steel
316L Stainless Steel	ϕ60 × 0.8	1.2	5 balls	Beryllium Bronze QBe2	Dual-cavity conformal	Special oil for stainless steel
Gr.2 Pure Titanium	ϕ50 × 1.0	1.5	4 balls	Beryllium Bronze QBe2	Anti-slip serrated + dual-cavity conformal	Chlorinated paraffin oil for titanium alloy
Gr.9 Titanium Alloy	ϕ50 × 0.8	2.0	5 balls	Beryllium Bronze QBe2	Dual-cavity conformal	Chlorinated paraffin oil for titanium alloy

5.2 Key Geometric Parameter Quick Reference Table

Parameter	Symbol	Recommended Range	Influence
Relative bending radius	R/D	1.0 ~ 2.0	Smaller value means higher forming difficulty
Relative wall thickness	t/D	0.015 ~ 0.05	Smaller value leads to harder forming
Mandrel clearance	c	0.15 ~ 0.25 mm	Excessive clearance causes collapse; insufficient clearance scratches tube surface
Mandrel overhang	e	(1/3 ~ 2/3)·D	Controls outer wall thinning rate
Wiper die contact length	Lw	2 ~ 3·D	Determines wrinkle suppression performance
Effective clamping length	Lc	≥ 2·D (standard) or ≥ 0.5·D with conformal cavity	Judges whether clamping sliding occurs during bending
Booster speed / bending speed ratio	v_boost / v_bend	0.95 ~ 1.05	Balances outer wall thinning degree

5.3 Common Defect Diagnosis and Countermeasures

Defect Phenomenon	Possible Causes	Solutions
Outer wall cracking	Excessive mandrel overhang / Insufficient booster force	Reduce mandrel overhang, increase booster thrust
Inner wall wrinkling	Excessive wiper die clearance / Backward offset position	Re-grind wiper tip, shift forward by 0.1 ~ 0.2 mm
Cross-section collapse	Insufficient mandrel balls / Excessive mandrel clearance	Add more ball joints, reduce mandrel clearance
Tube surface scratching	Insufficient lubrication / Rough die surface	Switch to extreme pressure oil, mirror polish dies
Clamp sliding	Insufficient clamping length / Low friction coefficient	Adopt anti-slip serrated or dual-cavity conformal clamp die
Insufficient bending angle	Insufficient springback compensation	Add 2 ~ 5° overbending compensation
Titanium alloy surface discoloration	Excessive forming temperature / Broken lubrication film	Reduce bending speed, strengthen cooling & lubrication

6. Integrated Forming Process Flow and Quality Control

6.1 Complete Process Flow

The complete manufacturing process of integrated weld-free exhaust pipes is as follows:

① Blanking (laser cutting to fixed length ± 0.5 mm)

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② End chamfering and deburring

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③ Inner and outer wall cleaning and degreasing

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④ Coating bending oil (titanium alloy dip coating)

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⑤ Loading into CNC RDB tube bender, aligned with the first positioning datum

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⑥ Sequential execution of N bending steps (each step: clamping → bending → loosening → feeding & indexing)

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⑦ Blanking, end shaping

↓

⑧ Quality inspection (CMM + endoscopy)

↓

⑨ Surface treatment (passivation / electropolishing / anodization)

↓

⑩ Warehousing

6.2 Three Key Synchronized Actions of Tube Bender

Within a single bending step, the machine must achieve strict synchronization of three major actions:

Action	Executing Component	Key Control Variables
Bend	Spindle + Bending Die	Angle, Speed, Torque
Boost	Booster Carriage	Booster Force, Booster Speed
Clamp	Clamp Die	Clamping Pressure, Opening & Closing Timing

Lack of synchronization among the three will directly cause: outer wall cracking (insufficient boosting), inner wall wrinkling (excessive boosting), or surface scratching (wrong clamping timing). It is recommended to use CNC RDB models with torque closed-loop and force-controlled boosting.

6.3 Quality Control Metrics (QC Metrics)

Inspection Item	Testing Method	Acceptance Criterion
Outer Wall Thinning Rate	Ultrasonic Thickness Gauge / Section Cutting	≤ 20%
Inner Wrinkle Height	Endoscope + Optical Measurement	≤ 0.05·t
Cross-Section Ovality	Coordinate Measuring Machine (CMM)	≤ 5%
Bending Angle Accuracy	Coordinate Measuring Machine (CMM)	± 0.3°
Overall Length Dimension	Coordinate Measuring Machine (CMM)	± 0.5 mm
Surface Roughness	Roughness Tester	Ra ≤ 1.6 μm
Surface Scratches	Visual Inspection + 10× Magnifier	No visible scratches to naked eye

7. Economic and Industrialization Significance

7.1 Unit Cost Comparison (Taking a typical motorcycle middle exhaust pipe as an example)

Cost Item	Welding Process	Integrated One-Piece Process	Variation
Raw Material	100% (Baseline)	105% (+5%)	+5%
Tube Bending / Welding Labor Time	45 min	8 min	−82%
Welding Consumables (Shielding Gas)	Required	None	−100%
Shaping / Grinding Labor Time	20 min	3 min	−85%
Air Tightness Leak Test	Mandatory	Eliminated	−100%
Defect Rate	5 ~ 8%	1 ~ 2%	−70%
Total Unit Comprehensive Cost	100%	65 ~ 75%	−25 ~ 35%

7.2 Performance and Appearance Gains

Back pressure reduction: The weld inner wall protrusion disappears, and the gas flow loss decreases by 3 ~ 8%;

Fatigue life: No heat-affected zone, measured fatigue cycles on the test bench improved by 40 ~ 60%;

Corrosion resistance life: Eliminates the sensitization zone, salt spray test life improved by 2 ~ 3 times;

Appearance quality: The entire tube mirror consistency, directly matching the aesthetic requirements of high-end models;

Lightweighting: Thinner wall materials can be used, reducing the weight of the entire tube by 8 ~ 15%.

7.3 Strategic Significance

For tube bender manufacturers, whether they can provide a complete solution for "whole tube integrated forming" has evolved from an optional advantage into a ticket to enter the high-end exhaust system supply chain. The five key technologies described in this white paper have all been verified and matured in actual production by SANCO GROUP, and can be used as a direct reference for production line upgrades by OEMs / exhaust system Tier 1 suppliers.

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8. Conclusion and Outlook

This white paper systematically discusses the integrated weld-free rotary draw bending forming solution for motorcycle/automobile thin-walled stainless steel/titanium alloy exhaust pipes under extreme conditions of small bending radius and short straight sections. The core conclusions are as follows:

1. Traditional welding process Has systematic defects in five dimensions: corrosion, fatigue, flow field, appearance, and cost, which are inconsistent with the development trend of high-end exhaust systems;

2. Through the collaborative application of five key technologies: C12 carbide bending die, multi-ball flexible mandrel, copper wiper die, anti-slip serrated clamping die, and dual-layer conformal clamping die, integrated forming can be achieved in extreme conditions of $R/D \le 1.5$, $t/D \le 0.05$, and straight section $L \rightarrow 0$;

3. Dual-layer conformal clamping die is an original technical solution for solving clamping challenges of short straight sections, with significant engineering value and promotion significance;

4. Integrated solution decreases overall cost by 25 ~ 35% compared to traditional welding solutions, while product performance and appearance are comprehensively improved.

Future Outlook:

Intelligentization: integrate online visual inspection and adaptive closed-loop compensation to achieve "zero-debugging" changeover;

Heat-assisted: explore induction heating assisted bending to further reduce the R/D limit to 0.8D;

Simulation-driven: whole-process CAE simulation to optimize mandrel lead and boosting curve, shortening the trial die cycle;

Green manufacturing: eliminate welding and grinding steps through integrated forming, achieving a substantial reduction in VOC emissions during the manufacturing process.

The era of integrated weld-free exhaust pipes has arrived. SANCO GROUP (www.sancomachine.com) is willing to join hands with global exhaust system manufacturers to jointly promote this transformation.

Appendix A: Engineering Video Demonstration (with QR code placeholder)

This white paper has reserved 5 placeholders for engineering demonstration videos throughout the text, to be supplemented by subsequent field filming. QR codes can host videos via object storage services such as Alibaba Cloud OSS / Tencent Cloud COS, and use QR code generators (Recommended: Caoliao QR Code / QR Code Monkey) to bind short links. Suggested video specifications: 1080P resolution, MP4 format, 30 ~ 90 s duration per segment.

No.	Video Topic	Suggested Content	Corresponding Chapter	QR Code Position
V-01	Performance Comparison: Welded vs One-Piece Forming	Weld section cutting + backpressure bench test data	§1.3	[QR]
V-02	Assembly & Commissioning of C12 Dies	Die installation, centering & trial bending	§4.1	[QR]
V-03	Working Process of Multi-Ball Mandrel	Shooting via transparent mold or endoscope	§4.2	[QR]
V-04	On-site Adjustment of Wiper Die	Clearance adjustment with feeler gauge + effect comparison	§4.3	[QR]
V-05	Bending Demonstration with Dual-Cavity Conformal Clamp Die	Full process from feeding to finished product	§4.4	[QR]

Symbol / Abbreviation	Definition	Unit
D	Tube outer diameter	mm
t	Tube wall thickness	mm
R	Bending centerline radius	mm
R/D	Relative bending radius	—
t/D	Relative wall thickness	—
L	Straight segment length between two bends	mm
θ	Bending angle	° or rad
ε_{max}	Maximum tensile strain of outer wall	—
σ_{cr}	Critical wrinkling stress	MPa
F_t	Tangential drawing force during bending	N
F_{clamp}	Clamping force	N
μ	Friction coefficient	—
RDB	Rotary Draw Bending	—
HAZ	Heat Affected Zone	—
WC-Co	Tungsten-cobalt cemented carbide	—
QBe2	Beryllium bronze grade	—
QAl9-4	Aluminum bronze grade	—
DLC	Diamond-Like Carbon coating	—

Appendix B: Symbols and Glossary

References

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